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A MAGNETIC REFERENCE UNIT USING PERMAMENT MAGNET FLUX

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WILLIAM E. SIMPSON

A MAGNETIC REFERENCE UNIT
USING
PERMANENT MAGNET FLUX

by

William Eugene Simpson

Lieutenant, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

United States Naval Postgraduate School
Monterey, California

1955

Thesis
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This work is accepted as fulfilling
the thesis requirements for the degree of
MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

from the
United States Naval Postgraduate School

PREFACE

The purpose of this paper is to present to the reader the theory of operation, design, and construction techniques of a magnetic reference unit which uses a reference flux produced by a dependable permanent-magnet as a basic reference. The basic development work on this device was accomplished at the U.S. Naval Ordnance Test Station, Inyokern, China Lake, California. The laboratory work and much of the research which contributed to the writing of this thesis was done at the Pacific Coast Division, Aerovox Corporation, Monrovia, California, during the 1955 winter term.

The writer wishes to express his appreciation to all those of the Pacific Coast Division, Aerovox Corporation, who provided guidance and assistance. In particular, thanks is expressed to Mr. Kenneth Goodman, Mr. Joe Chun and Mr. Robert D. Hallock. Sincere appreciation is also expressed to Mr. William Woodworth and Mr. Lang Sykes of the U.S. Naval Ordnance Test Station, Inyokern, China Lake, California for their technical assistance and helpful suggestions. The writer wishes to express his deepest appreciation to his faculty advisor, Professor G. R. Giet, for his guidance.

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TABLE OF SYMBOLS AND ABBREVIATIONS

(Listed in the order of their use in the text)

d-c	Direct current.
a-c	Alternating current.
e_A	Instantaneous voltage across coil A.
e_B	Instantaneous voltage across coil B.
N_g	Number of turns on the gate winding.
ϕ	Flux in maxwells.
ϕ_s	Saturation flux in maxwells.
I_E	Exciting current, average value.
$I_{L\,max}$	Maximum value of the load current.
E_m	Peak value of the sinusoidal supply voltage.
R_L	Load resistance.
I_c	Control current, average value.
α	Saturation angle.
NI	Ampere - turns.
E_{rms}	Root mean square value of the sinusoidal voltage.
f	Frequency in cycles per second.
t	Time.
B	Flux density in gauss.
H	Magnetizing force in oersteds. (1 oersted = 2.021 NI per inch)
mmf	Magnetomotive force.
N_c	Number of turns on the control winding.
I_o	Average value of the output error current from the magnetic reference unit.

R_o	Input resistance to the amplifier or control device.
ω	Angular frequency in radians per second.
L	Inductance in henries.
F_m	Magnetomotive force induced in to the core by the permanent-magnet flux.
i_d	Change of current in the gate windings of the magnetic reference unit required to saturate the core when there is a net direct mmf across the end leg of the core.
i_o	A-c supply current just large enough to saturate the core of the magnetic reference unit.
R_ℓ	D-c resistance around each loop of the symmetrical gate winding circuits of the magnetic reference unit.
R_e	An equivalent d-c resistance defined by equation 21.
R_g	Sum of the d-c resistance of the gate windings and the forward resistance of the crystal diodes.
u	Permeability of the magnetic material evaluated at the appropriate maximum alternating flux density B_{max}.
a_i	Cross section of the iron in the core.
a_a	Effective cross section of the air gap.
l_a	Length of the air gap.
l_i	Mean length of the magnetic circuit in the iron core.
K	A constant defined by equation 27.
H_c	Coercive force of a permanent-magnet.
B_r	Residual flux density of a permanent-magnet.
ma	Milliamperes.

CHAPTER I

INTRODUCTION

The magnetic reference unit discussed in this paper is an application of a saturable core reactor device combined with the stability of a permanent-magnet to produce a static reference for sources of constant voltage or current for use with magnetic amplifier and transistor circuits or for reference purposes in radar and computer systems. The reference unit is an error detector device which is used in a closed feedback loop with a high gain magnetic amplifier to form a source of constant voltage or current.

The application of saturable core reactors to the regulation of electric circuits is not a new device, being first applied to this purpose in 1901 by C.F. Burgess and B. Frankenfield. [10]. Amplification properties of a saturable core device was published by E.F.W. Alexanderson in 1916. Although saturable core devices have been used especially in the field of control of electrical machinery during the past fifty years, the Germans work in the field of magnetic amplifiers during World War II can possibly be considered the rebirth of the magnetic amplifier, since they improved the efficiency and time response and broadened its field of application. [18]. The revolutionary development of magnetic amplifiers and its application into the field of electronics in recent years has been due to the development of nickel-iron-alloy core materials and to improved rectifiers, [2], and to the efforts of a very large group of investigators who have contributed to the field. [13].

The outstanding quality of magnetic amplifiers and other static saturable core devices, especially for application in Naval Electronics, is reliability. The reliability of saturable core reactors is comparable to that of a conventional transformer and the life of a unit containing rectifiers may be expected to be governed by the rectifiers used. Germanium and silicon crystal rectifiers normally used in low powered units are rated at 60,000 hours for normal operational requirements. [18]. This improvement in reliability over electron tube circuits has resulted in considerable effort in the application of saturable core reactor circuits to the field of electronic devices where their performance equals that of electron tube circuits. Their application has extended into development for application to radio, radar, and sonar equipment and into applications in computer circuits. [4, 5, 18]. In many of the applications a reference is required for regulated output voltages for biasing purposes or to provide a stable reference voltage source for circuit applications. In electronic circuits the voltage drop across a gas discharge tube is a commonly used reference. Non-linear resistor and non-linear heated metallic elements have also been used as reference devices. However, these devices often do not satisfy the desirable characteristics of a low impedance device that will provide a reasonably stable reference with high reliability for static magnetic circuits subjected to shock, vibration and wide temperature ranges. The magnetic reference unit used in conjunction with a high gain magnetic amplifier is presented as an approach to satisfying these requirements. As an aid in understanding the operation and construction of a source of regulated voltage composed

of a magnetic reference unit used in conjunction with a high gain magnetic amplifier, chapters presenting the theory of operation of a magnetic amplifier, a magnetic reference unit and the design considerations of a magnetic reference unit are included.

CHAPTER II

THEORY OF OPERATION OF SATURABLE REACTORS

Both the magnetic amplifier and the magnetic reference unit discussed in this paper are saturable reactor devices. In a paper by William H. Elliot [7] a saturable reactor, which may be a simple saturable reactor, saturable-core reactor, d-c controllable reactor, saturable transformer or a magnetic amplifier are defined as

> iron-cored inductors whose a-c winding impedance is controlled through saturation of the core effected by a magnetomotive force under control of an auxiliary d-c winding.
>
> The magnetic amplifier is a device using saturable reactors either alone or in combination with other circuit elements to obtain amplification or provide control.

While the magnetic reference unit could possibly be used with other types of high gain amplifiers to furnish a current or voltage supply, considerations of current gain, power output required and reliability are satisfied by a high gain magnetic amplifier. During the past fifty years there have been many forms of magnetic amplifiers described and many of these types have been codified according to an orderly system presented by James G. Miles. [14]. The amplifier requirements for use with the magnetic reference unit appear to best be satisfied by the self-saturated magnetic amplifier utilizing positive feedback. Therefore the following discussion will be limited to the elementary magnetic amplifier for the fundamental theory of operation and to the self-saturating circuit.

1. The elementary magnetic amplifier.

The elementary magnetic amplifier of a simple series connection is shown in Figures 1A and 1B and consists of two ferromagnetic circuits

wound with two identical load current or "gate" windings and a common control current winding. [11, 9]. To avoid the induction of the fundamental of the supply voltage into the d-c control winding, the gate windings are connected so that the load current will tend to produce fluxes in the opposite direction through the control winding. With the gate windings connected series aiding and the control windings connected series opposing as illustrated in Figure 1C, the fundamental and the odd harmonics of the supply voltage induced in the control windings cancel each other. However, the even harmonics circulate in the low impedance control circuit, giving "natural" magnetization of the core. [6, 10]. The gate windings are shown in series, but they could also be connected in parallel. The magnetic circuit may be on a single three leg core, Figure 1A, or on separate toroidal cores, Figure 1B. The three leg single core has the disadvantage that leakage flux has some effect upon the magnetic amplifier.

In order to simplify the explanation of the mode of operation, it is helpful if certain assumptions are made: the magnetization curve possesses an idealized shape, the load is a resistive load, the control circuit resistance is relatively low and a pure direct current is applied to the control windings, and the a-c supply voltage is a sinusoidal voltage.

From Faraday's Law of Magnetic Induction the relation between the voltages across the gate windings of the series connection shown in Figure 1C and the supply voltage may be expressed by

$$e_A = N_g \frac{d\phi}{dt} \times 10^{-8} \quad (e_A \text{ in volts}, \phi \text{ in maxwells}) \tag{1}$$

$$e_B = N_g \frac{d\phi}{dt} \times 10^{-8} \quad (e_A \text{ in volts}, \phi \text{ in maxwells}) \tag{2}$$

or the change in core flux may be given by

$$\Delta \phi_A = \frac{10^8}{N_g} \int e_A \, dt \tag{3}$$

$$\Delta \phi_B = \frac{10^8}{N_g} \int e_A \, dt \tag{4}$$

where N_g is the number of turns of the gate winding for each core. Since the permeability of the core material used in d-c controlled saturable reactors is large when the core is unsaturated, the supply voltage will be divided across e_A and e_B (this neglects a small $I_E R_L$ drop across the load due to the exciting current). When the cores go into saturation at points c and g of Figure 2A, then the voltage drop across the load resistor is equal to the supply voltage. This implies that the theoretical maximum average current that can flow through the load, assuming both cores completely saturated over the full cycle of the supply sinusoidal voltage, is

$$I_{L\,max} = \frac{2}{\pi} \frac{E_m}{R_L} \tag{5}$$

For a negligible value of control current (assume I_c is zero) and a moderate value of supply voltage which does not cause saturation of the cores, the voltage drop across the gate windings will be equal to the supply voltage and the output current will be zero due to the high reac-

tive impedance across the coils. For a sinusoidal voltage the flux variation will be a cosine function (equations 3 and 4) which varies along the path f-a-b-a-f of Figure 2A. The voltage and flux wave form relations are shown in dotted lines in Figure 3. If the supply voltage is increased in magnitude until the flux in Figure 2A is varying along the path h-a-d-a-h the cores will saturate at some angle α and $\alpha + \pi$ of the supply voltage, normally termed the "firing" or saturation angle. When the core saturates, further change of flux in the core can no longer take place so e_A and e_B drop essentially to zero, load current of $i_L = \frac{e}{R_L}$ flows and the supply voltage is dropped across the load resistor until the core returns to the unsaturated state. The peak value of the supply voltage and the number of turns on the gate windings are normally adjusted so that the flux varies just to the saturation point of the flux path with no control current flowing, that is along path g-a-c of Figure 2A.

Referring to Figure 1B, we note that for control current flowing, flux is introduced into core A and core B in opposite directions.

$$NI = N_g I_L + N_c I_c \quad \text{for core A} \tag{6}$$

$$NI = N_g I_L - N_c I_c \quad \text{for core B} \tag{7}$$

Thus we would expect core A to be going into saturation on the half cycle when core B is coming out of saturation when control current is flowing. With core A in saturation, the gate winding of core A can no longer support a voltage e_A, Figure 1C, and its control winding has no impedance. Neglecting any control circuit impedance, the control winding of core B is then short circuited, causing a collapse of voltage e_B also.

With the collapse of voltages across the gate windings, a load current flows until core A comes out of saturation. This flow of load current through the gate winding of core B induces a current $i_c = i_L \frac{N_g}{N_c}$ into the control circuit. With neither core in saturation, the gate windings present a high impedance in the load circuit and a negligible load current flows in the circuit. Assuming the ideal magnetization curve, Figure 2A, both the load current and the control current are zero when neither core is in saturation. Similarly on the other half cycle of the supply voltage, core B goes into saturation at $\alpha + \pi$ and can no longer support the voltage e_B. With core B in saturation the control winding of core A is short circuited causing a collapse of voltage e_A. With the collapse of the coil voltage, load current again flows and the gate winding of coil A induces current in the control winding in the same direction as that induced by coil B due to the control windings being connected series opposing. Thus there are two unidirectional pulses of current in the control circuit for each full cycle of the supply voltage. The average value of these even harmonic current pulses is equal to the d-c level of control current which is determined by the control circuit d-c voltage and the control circuit resistance. This control current changes the average flux level in each core. For instance, referring to Figure 2A, a control voltage level can set ϕ_o of core A to point b and ϕ_o of core B to point f, where ϕ_o represents the average flux level for the core over the flux cycle. The flux of core A would traverse the path f-b-c-e-f and that of core B the path b-f-g-j-b over a supply voltage cycle.

Noting the solid line wave forms of Figure 3 over one cycle of operation, let us assume as a starting point $\phi_B = -\phi_S$, core B flux rising out of saturation at $\theta = 0$ for a supply voltage of $e = E_m \sin \theta$. Note that the average value of the flux for each core is no longer zero due to the control current flowing with an impressed d-c control voltage, E_c. From $0 \leq \theta < \alpha$ neither core is in saturation and both the load current and control current are instantaneously zero. When $\theta = \alpha$ the flux of core A reaches point c on the magnetization curve. Now $\phi_A = +\phi_S$ with core A in saturation until $\theta = \pi$ and load current flows over this interval inducing a current in the control circuit. Both cores are unsaturated for the interval $\pi < \theta < \alpha + \pi$ and again the load and control currents are zero. At $\theta = \alpha + \pi$ the flux of core B reaches point g on the magnetization curve, causing $\theta_B = -\theta_S$ with core B remaining in saturation until $\theta = 2\pi$. Load current will flow over the interval that core B is in saturation, inducting a current in the control circuit. The foregoing cycle of events recurs periodically with the frequency of the supply voltage. The a-c supply voltage is necessary to furnish a power source and to carry the core flux into and out of saturation. The d-c control current level determines the average core flux, the saturation angle α, and thus controls the magnitude of the load current. The rectified average value of the load current and the average value of the control current are related by

$$I_c = \text{Averge}\,(i_c) = \text{Average}\left(\frac{i_L N_g}{N_c}\right) = \frac{I_L N_g}{N_c} \qquad (8)$$

within the limits of the permissible values for the load current (equation 5).

The control characteristics for the elementary magnetic amplifier, assuming idealized rectangular magnitization curve, is shown in Figure 4A. Figure 4B shows the control characteristics for a typical magnitization curve with hysteresis losses illustrated in Figure 2B. Note that the load current does not go to zero in Figure 2B, for an exciting current flows in the load circuit which does not change the flux level in the core material but overcomes the coercive forces of the core material and eddy current losses. The relation between the load current, the exciting current, and the saturation current is

$$I_L = I_E + I_{LS} \tag{9}$$

The exciting current is normally very small compared to the saturating current for good magnetic amplifier core materials and was neglected in the preceding idealized discussion. The round knee at the top of the control characteristics is caused by the similiar round knee of the magnitization curve. The power gain of the amplifier is given by

$$G = \frac{\text{useful load power}}{\text{control source power}} = \frac{I_L^2 R_L}{I_c^2 R_c} = \frac{N_c^2 R_L}{N_g^2 R_c} \tag{10}$$

The time constant of the amplifier is directly proportional to the gain of the amplifier and inversely proportional to the frequency of the power supply. The gain to time constant ratio for the elementary magnetic amplifier is theoretically a constant value of four cycles of the power supply frequency. [11]. Therefore the gain can only be increased at the price of an increase in the time constant of the amplifier.

Note in Figure 4B that the output current does not depend on the polarity of the control current, but only on its magnitude. The output may be made to depend on the polarity of the control current by the addition of a d-c winding called the "bias" winding to supplement the control winding and thus shift the $I_C = 0$ line of the control characteristics to the right as shown by the dotted line on Figure 4B, giving a quiescent operating point at point X. If the turns ratio of the control winding turns to gate winding turns is made large in order to obtain gain, the response time of the amplifier becomes very long. Because of this property, a normal procedure in the use of magnetic amplifiers is to make the ratio of control winding turns to gate winding turns approximately unity and utilize positive feedback to obtain the desired gain.

2. The effects of positive feedback.

The average power gain per cycle of the amplifier can be raised significantly by the use of positive current feedback. This feedback is usually accomplished in either one of two methods. The load current may be rectified and fed back on a separate feedback winding in the same polarity as the control winding to give external positive current feedback to the elementary series connected amplifier or by use of the self-saturating circuit in which the current feedback is accomplished by the use of rectifiers in parallel connected gate winding circuits. A method of utilizing external positive current feedback in the elementary series connected circuit is illustrated in Figure 5. With a low control circuit impedance the operation of the saturable reactor is the same as previously given except that the ampere-turns of the feedback winding assists the

control winding ampere-turns in equalizing the gate winding ampere-turns, thus reducing the required control winding ampere-turns by the number of feedback winding ampere-turns. The relationship between the control winding ampere-turns and the gate and feedback ampere-turns becomes,

$$I_c N_c = I_L N_g - I_f N_f$$

where $I_f = I_L$ for the series connection, so

$$I_c N_c = I_L N_g \left(1 - \frac{N_f}{N_g}\right) \tag{11}$$

and $\frac{N_f}{N_g}$ becomes the feedback factor.

The effect of positive current feedback on the control characteristic curves results in a skewing of the characteristic curve. This is illustrated graphically in Figures 6A and 6B. Also note that as the feedback factor approaches unity, near maximum output current is obtained with zero control current, whereas the load current was at a minimum value for zero control current in the elementary amplifier without feedback.

3. The self-saturating magnetic amplifier.

The number of feedback turns required to obtain a 100% positive feedback factor may be greatly reduced by the use of internal feedback in the amplifier, commonly referred to as a self-saturated magnetic amplifier or Amplistat[1]. A center-tap self-saturating circuit is illustrated in Figure 7. There are other self-saturated circuit configurations to meet various applications. [15].

---

[1] General Electric Co. Trade Mark

The center-tap circuit of Figure 7 is equivalent to the external feedback circuit of Figure 5 with 100% feedback. The self-saturated circuit permits better use of the winding area of the core, as fewer turns of wire are required to obtain comparable control characteristics. The actual shape of the control characteristic is influenced by the hysteresis loop of the core material and imperfections of the rectifiers, being adversely affected by slow saturation of the core material, hysteresis and eddy current losses, and back leakage of the rectifiers, With square hysteresis loop core material and negligible back leakage of the rectifiers, the maximum value of output current will be obtained with zero control current as illustrated in Figure 8. The wave shapes of the self-saturating magnetic amplifier closely resemble those of the previously discussed elementary magnetic amplifier but its mode of operation is somewhat different due to the effects of the feedback. In order to consider the mode of operation of the self-saturating circuit of Figure 7 refer to the wave forms of Figure 9. For explanation purposes, assume constant forward resistance and infinite back resistances for the rectifiers, low impedance control circuit, and rectangular dynamic hysteresis loops. It is also assumed that the air core inductive reactance of the saturated cores are negligible compared to the load resistance and the resistances are negligible compared to the inductive reactance when the cores are not saturated. The a-c voltage is sinusodial with a peak value of sufficient magnitude to cause a sinusodial flux swing equal to the saturation flux, i.e., $E_{rms} = 4.44 f \phi_s N_g 10^{-8}$.

With the circuit in steady state condition at time, t = 0, a

positive going voltage is applied to coil A and the flux of core A and core B are at point 1 on their respective dynamic B-H loops. A sharp rise of the small exciting current in coil A moves the operating point to point 2 where the flux change may take place in core A along the vertical sides of the B-H loop. This exciting current is very small compared to the load current. The gate voltage of coil A transforms into the control winding and induces a sharp rise of control current in the control circuit, since there is no flux change in core B as the operating point moves from points 2 to 3. As the rising line voltage is dropped across the inductive reactance of coil A, due to the change of the flux of core A in moving from points 3 to 4, the coil voltage, e_A, neglecting any voltage drop in the control circuit, is transformed into coil B, causing the flux of core B to reset to point 4. Current flow through coil B is prevented on this half cycle by the rectifier in the circuit. At operating point 4, the line voltage reaches the saturation angle α, core A goes into saturation and load current begins to flow through coil A. With core A in saturation, there is no longer a transformed voltage into the control circuit and the control current returns to zero, moving the operating point to point 5 on the B-H loops. Load current flows through coil A until the line to neutral voltage reaches zero, determining operating point 6 on the B-H loops. Similar action takes place on the next half cycle, with current flow through coil A being prevented by a rectifier and coil B controlling the load current and resetting the flux level in core A. The operation of the circuit is periodic with the applied a-c voltage.

The average value of the control current depends upon the d-c level of the control voltage source and the resistance of the control circuit as noted in the elementary magnetic amplifier circuit. It may be noted that with an average value of control current of zero the flux reset would be very small and near maximum load current would flow. The saturation angle α is determined by the peak value of the supply voltage and the d-c level of the control current. The output is therefore also sensitive to supply voltage change unless the self-saturated circuit is used in a push pull arrangement or a compensating voltage-sensitive bias winding is added to the circuit. [16].

For proper operation of the circuit it is important that the two cores have closely balanced magnetic properties so that the two cores reach saturation at corresponding saturation angles on the positive and negative half cycles. Any back current flow through the diodes will have a demagnetizing effect on the cores and reduce amplification. The reduction of gain due to a finite back current flow through the diodes may be compensated by the use of an external positive feedback winding. Since the back current flow through a diode has a demagnetizing effect on the core, it is important that the diodes also be matched for back resistance. The diodes are often shunted by a "spoiling" resistor to reduce the effect of change of diode back resistance with temperature and aging. Silicon diodes are now available, which have a very high back resistance over a large temperature range, that are an effective improvement for many magnetic amplifier circuit applications.

Self-saturated magnetic amplifiers also tend to lose control of the

current in circuits with a highly inductive load. With an inductive load, a decaying load current tends to flow in the rectifier of the gate winding circuit after the duty cycle has been completed, giving simultaneous conduction of load current by both rectifiers. This action is called "commutation" and may be overcome by shunting the inductive load with a capacitor or a commutation rectifier, which provides a return path for the inductive discharge. [16].

ELEMENTARY MAGNETIC AMPLIFIER CIRCUITS

SERIES CONNECTIONS

$R_c \ll R_L$

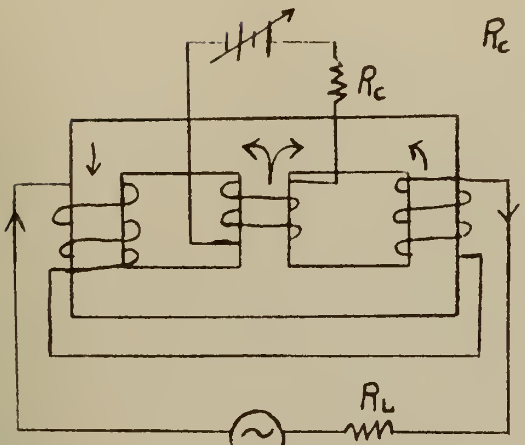


Figure 1A

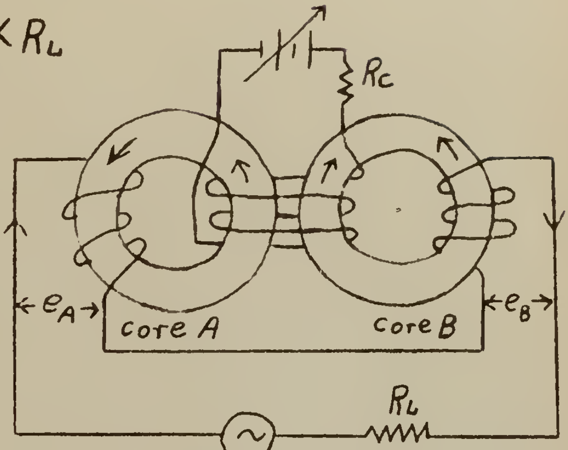


Figure 1B

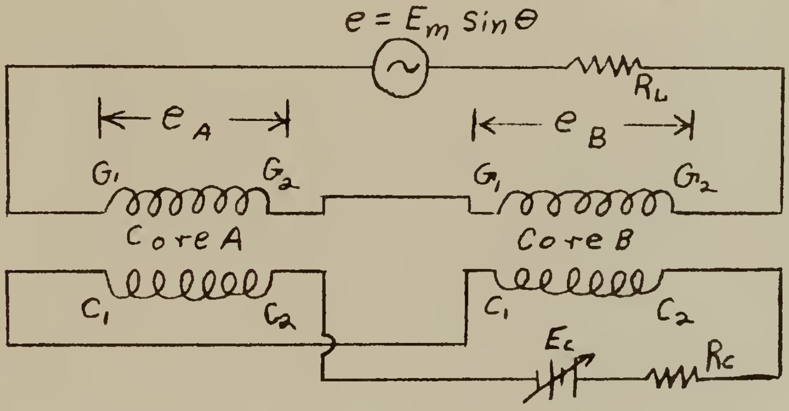


Figure 1C

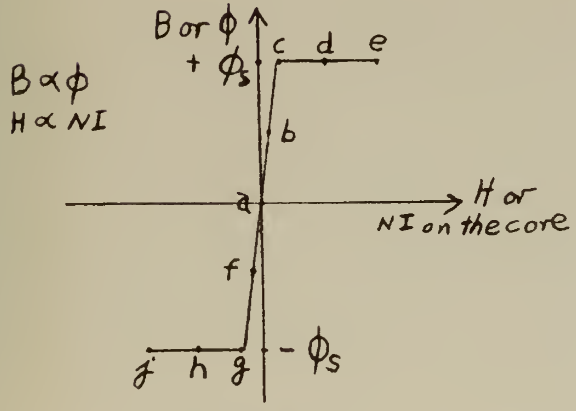


Figure 2A
Ideal magnetization curve

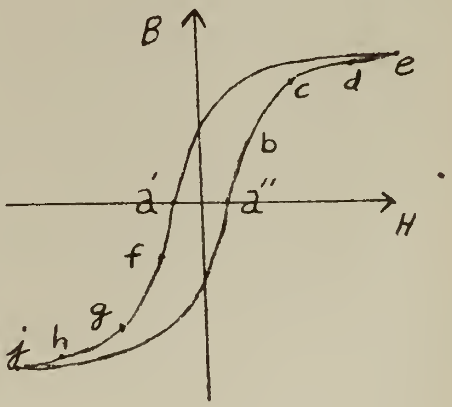


Figure 2B
A typical high permeability
core material magnetization curve

Theoretical wave forms for an elementary series connected d-c controlled saturable reactor with low control circuit impedance.

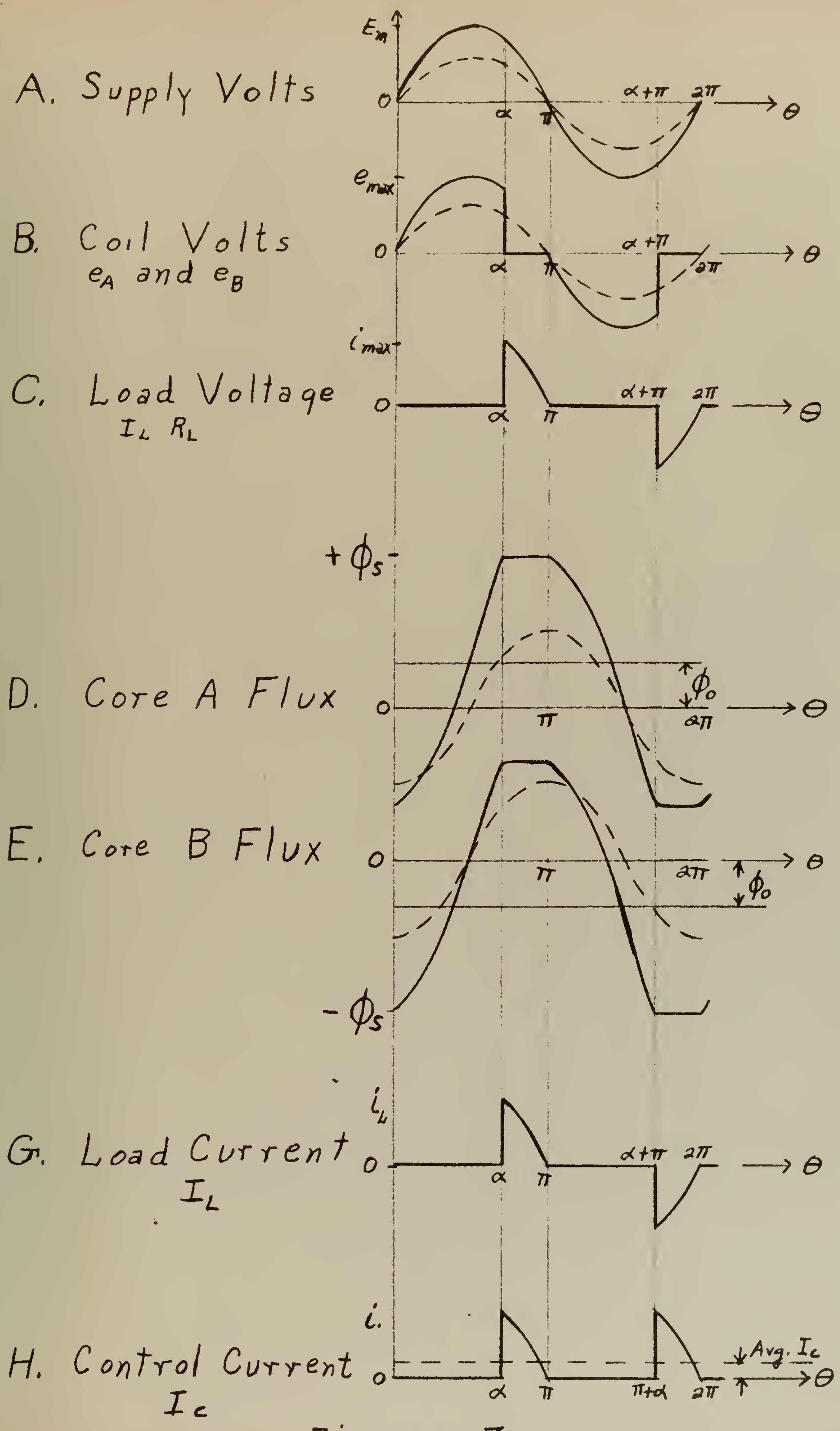


Figure 3

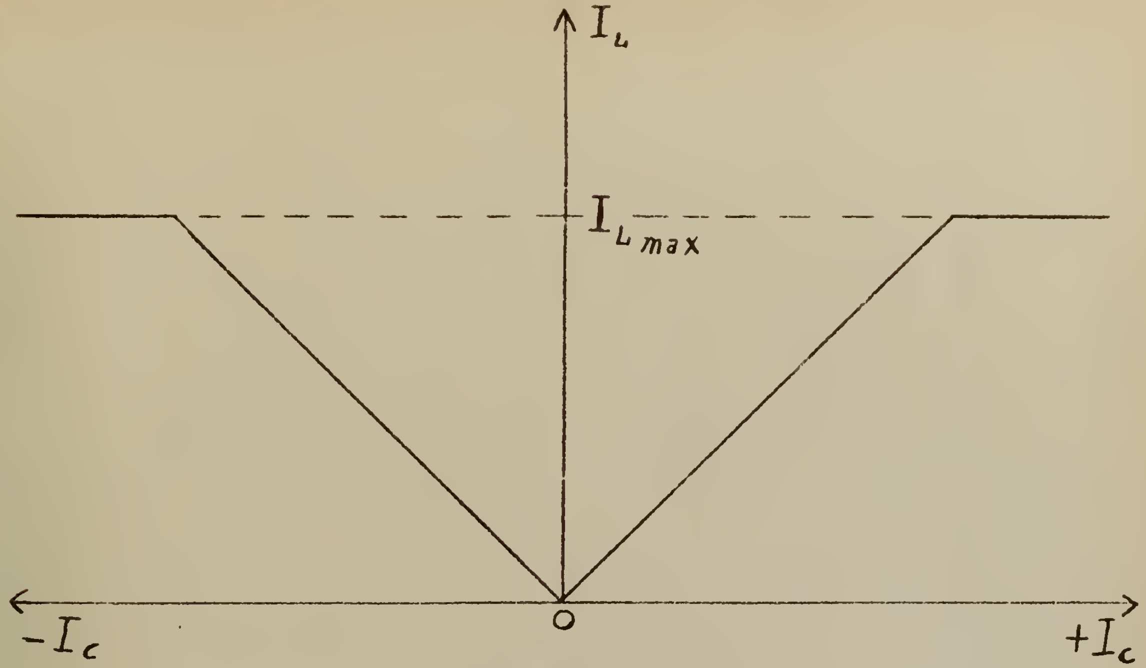


Figure 4A

Sketch of an idealized control characteristic

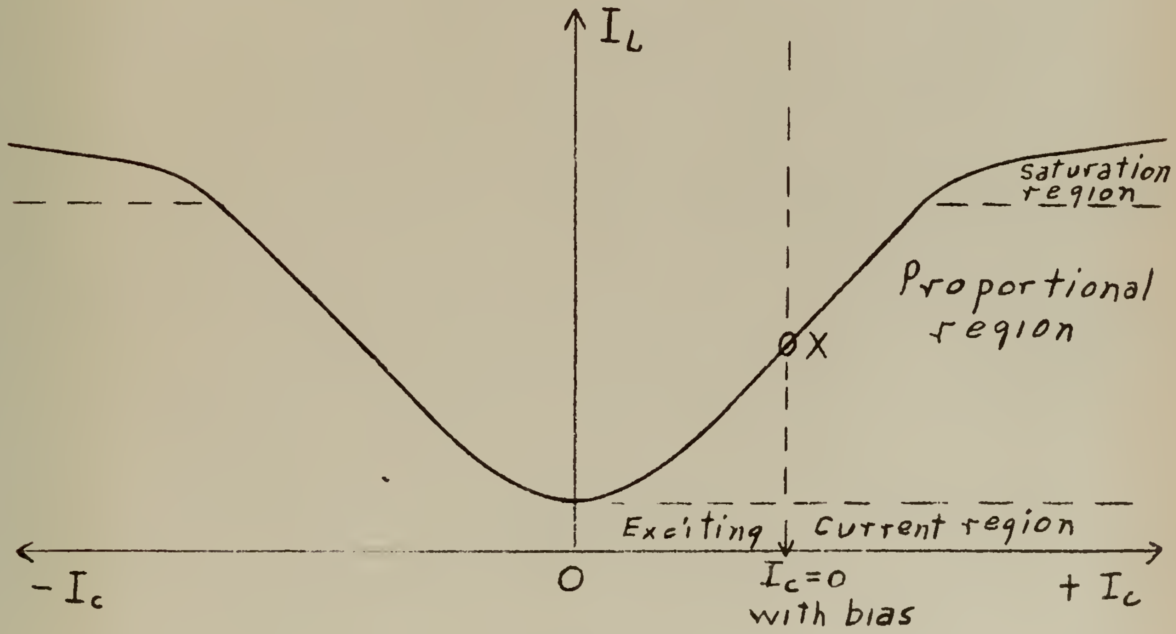


Figure 4B

Sketch of a typical control characteristic

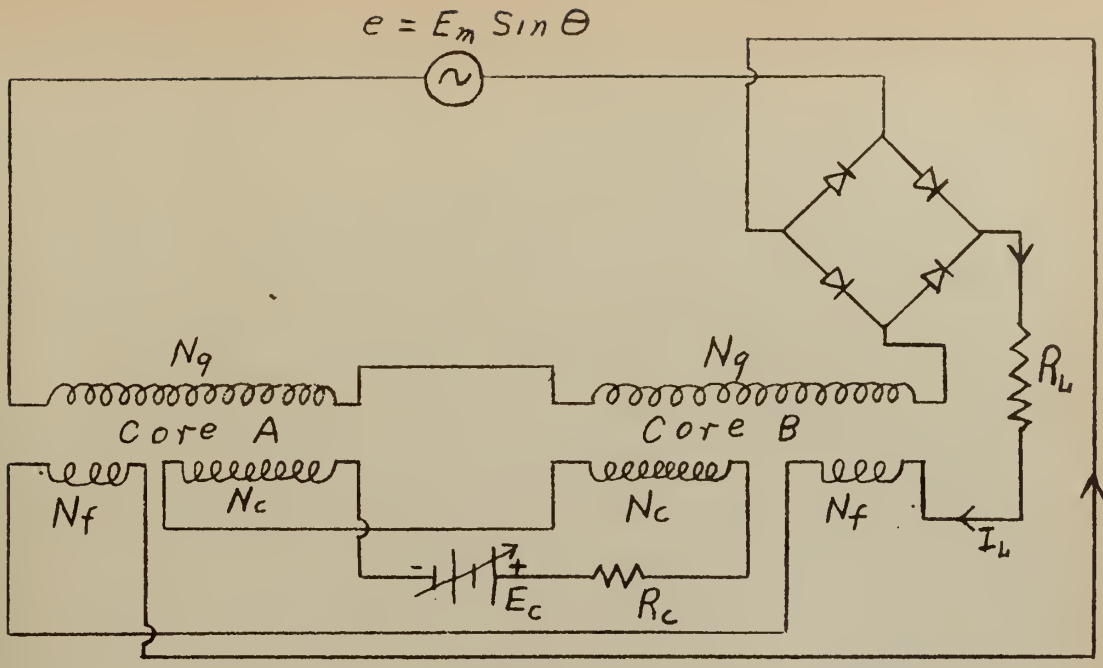


Figure 5

Elementary series connected magnetic amplifier with external feedback and d-c output

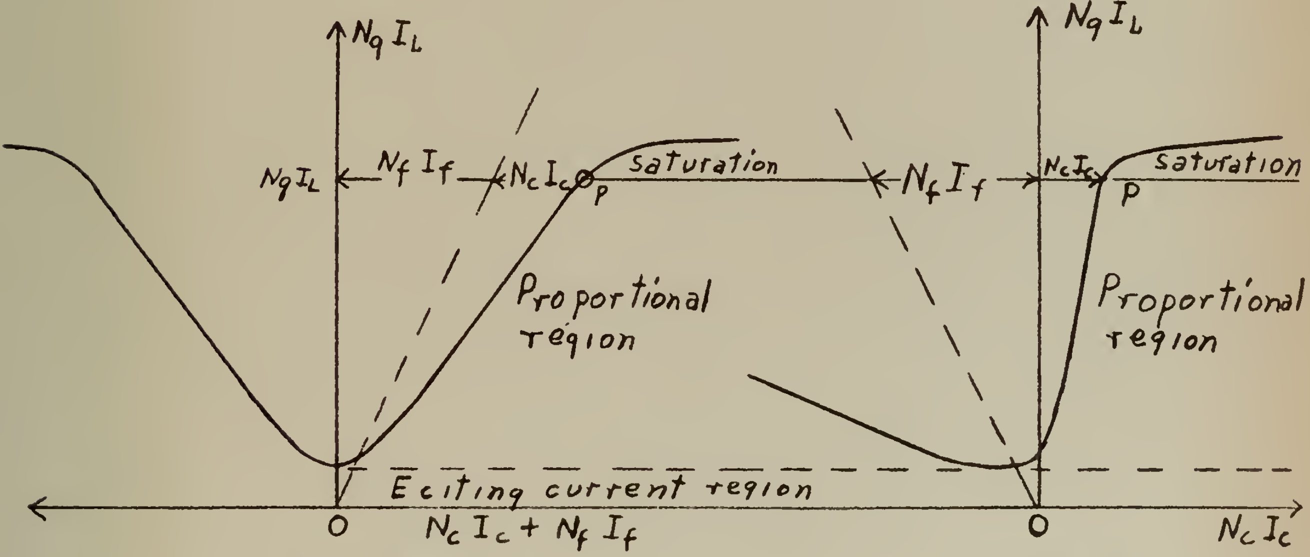


Figure 6A

Derivation curve

Figure 6B

Control characteristic

Sketch of the control characteristics of an elementary magnetic amplifier with external feedback.

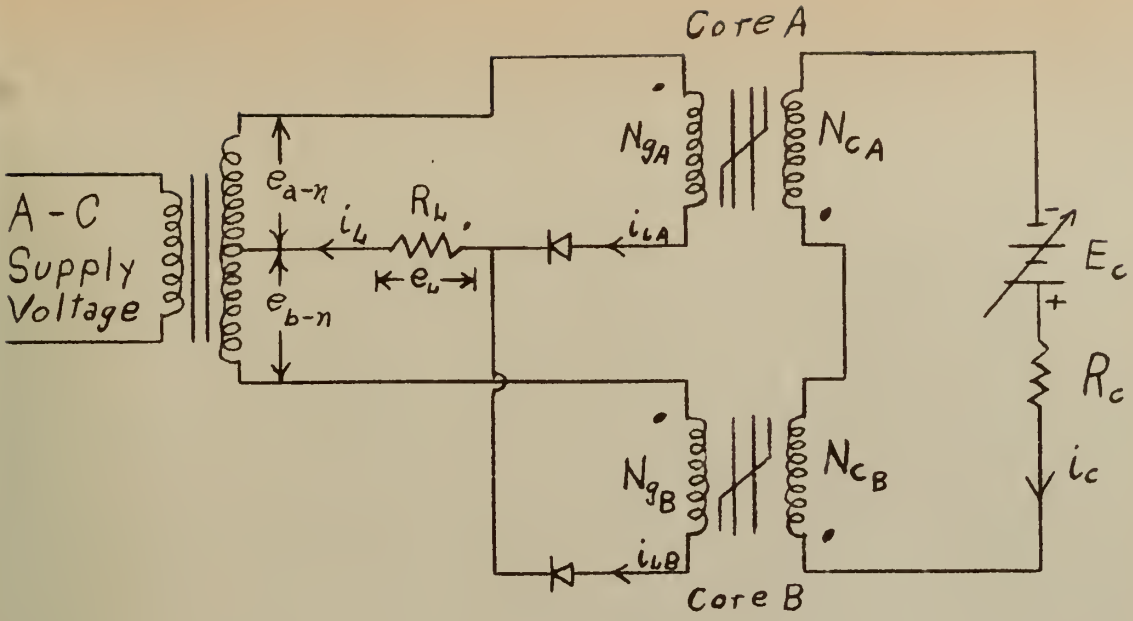


Figure 7

Basic center - tap self-saturating circuit with d-c output .

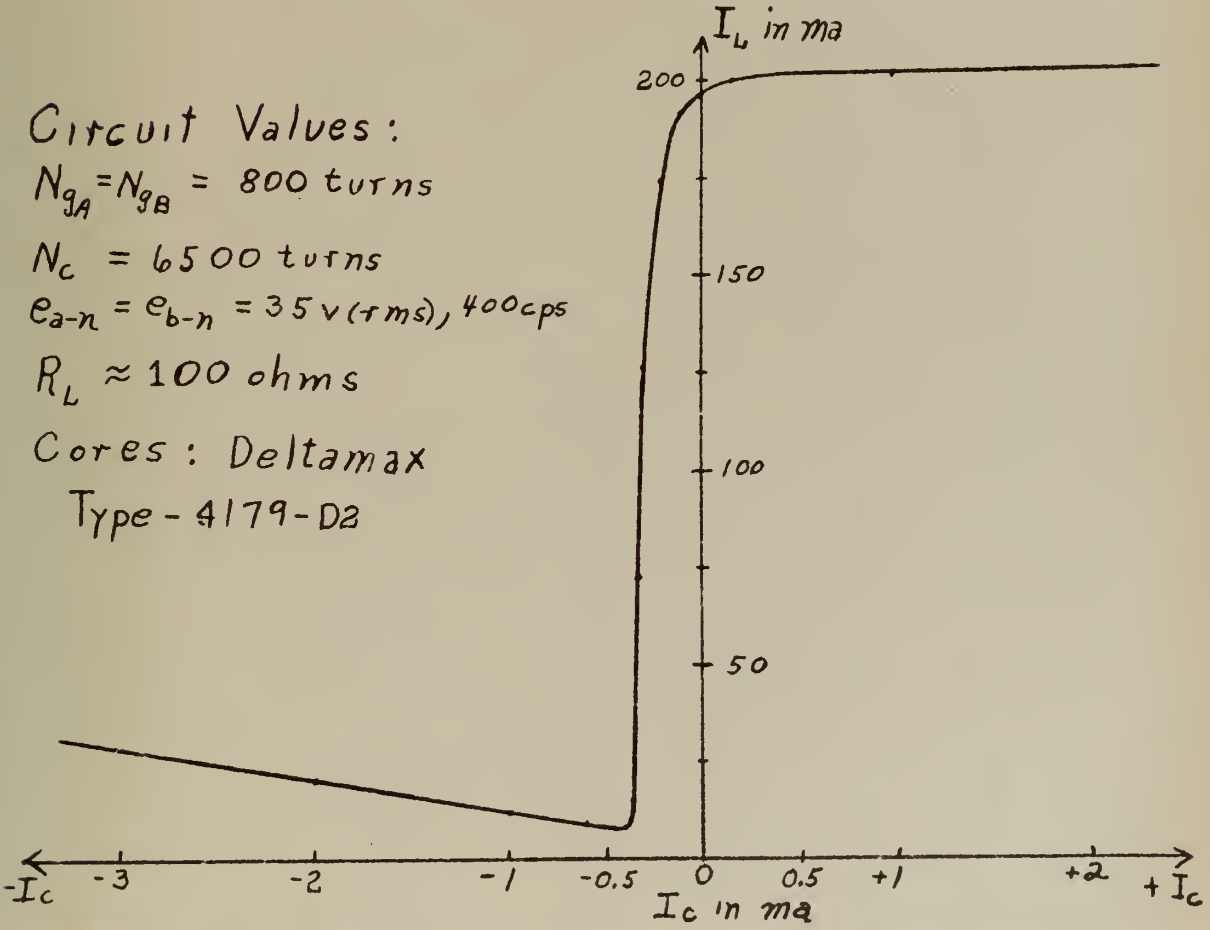


Figure 8 . Typical control characteristic for a self-saturated circuit with Deltamax cores.

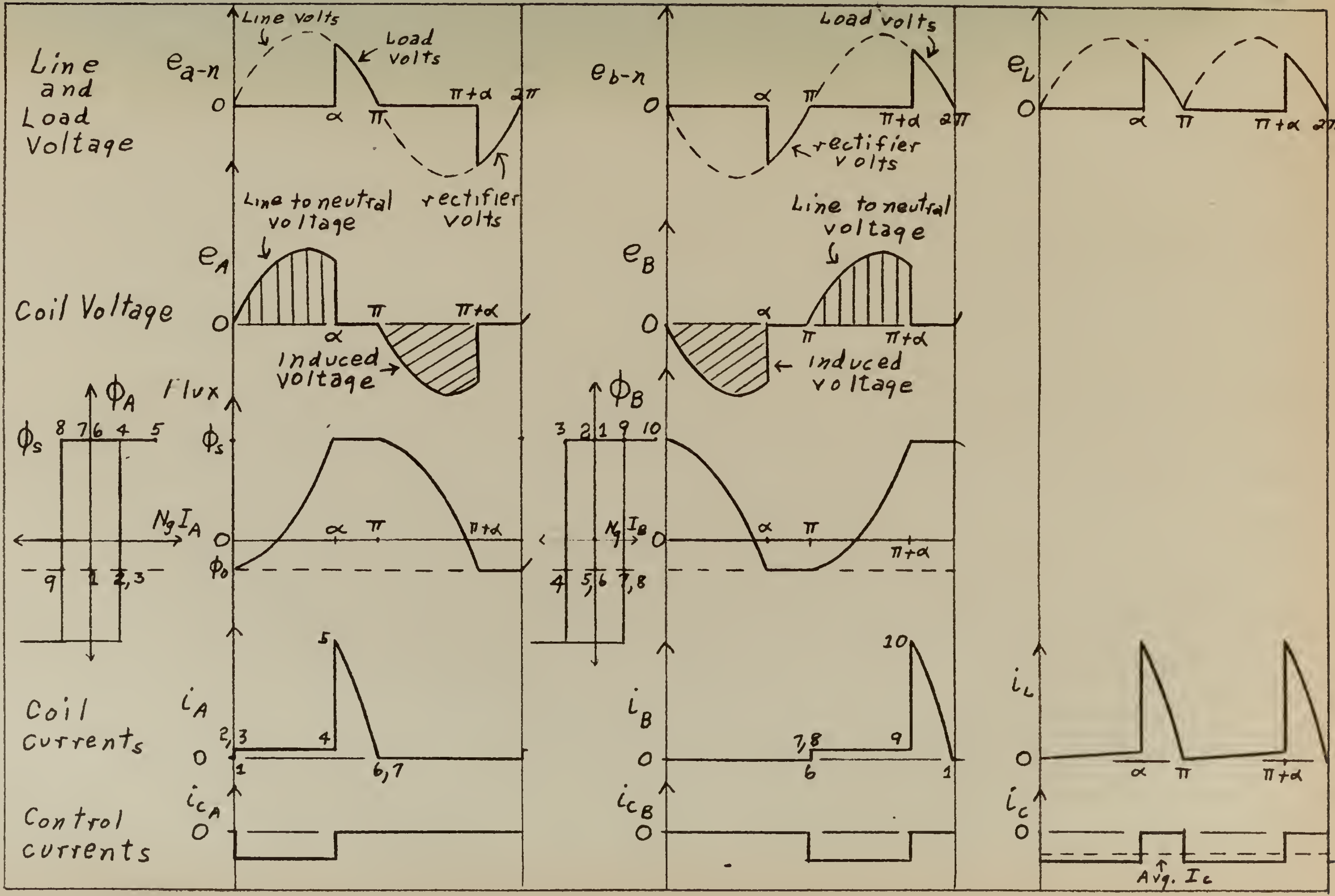


Figure 9. Waveforms for the self-saturated circuit.

CHAPTER III

A MAGNETIC REFERENCE UNIT

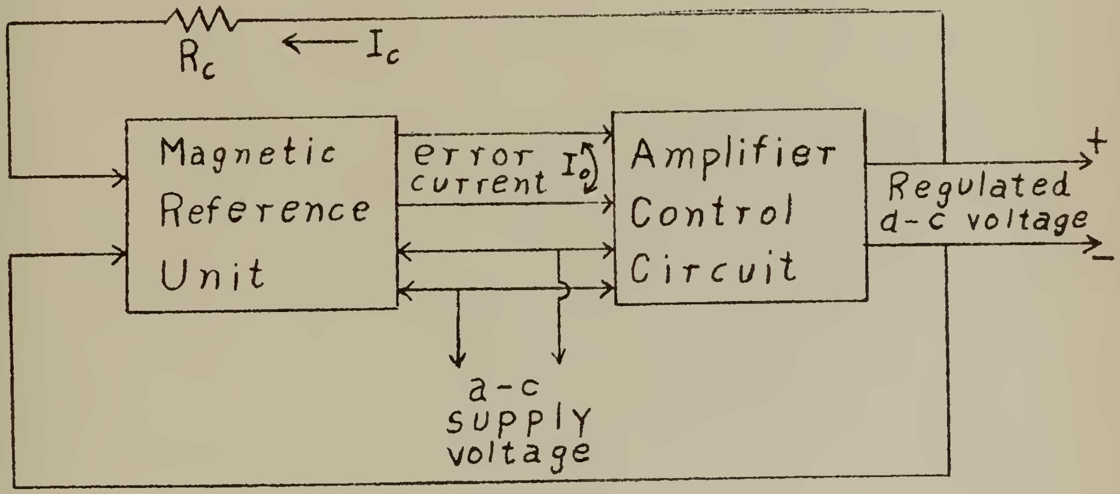
In regulation or control systems it is often necessary to compare the quantity to be controlled with a reference quantity, thus producing an error to actuate a correction device which tends to maintain the controlled quantity at a fixed value. In chapter I it was pointed out that several devices have been used for reference purposes. For use with magnetic amplifier circuits, it is often desirable to have a low impedance device which can be more easily matched with the low impedances usually found in these circuits and also provide equal reliability. Two static devices that may be used are a saturating transformer reference and a permanent - magnet biased saturable-core reactor. [16].

The saturating transformer is a transformer in which the input voltage is of sufficient magnitude to saturate the core on each half cycle. The area represented by the integral of the secondary voltage is a constant for a transformer constructed with square hysteresis loop core materials and supplied with a voltage of constant frequency. [8]. The basic reference property of this device depends on a saturation flux for the particular core used. If the frequency of the power source cannot be relied upon to remain constant, either compensation for the effect of frequency change must be incorporated or the permanent - magnet biased saturable-core reactor may be used. A permanent - magnet biased saturable reactor type of reference unit will be discussed and referred to specifically as "a magnetic reference unit".

1. Theory of Operation.

The mode of operation of the magnetic reference unit closely resembles the operation of the amplifiers discussed in Chapter II for flux variation of the cores, the primary difference being in circuit configuration and biasing. The circuit diagram of the magnetic reference unit is illustrated in Figure 10. It is composed of two symmetrical magnetic circuits utilizing a three leg magnetic core, a permanent-magnet across an air gap, a d-c control winding linking each magnetic circuit and two symmetrical gate winding circuits. The permanent-magnet developes in each magnetic circuit a mmf, which depends on the strength of the permanent-magnet, the reluctance of the shunting air gap, and the reluctance of the magnetic paths in the core material. The control windings, N_c, carrying a d-c current, I_c, develop a mmf which opposes the mmf developed by the permanent-magnet. The gate windings, N_g, are connected in parallel across an a-c supply voltage which has a peak value of sufficient magnitude to saturate each core leg. If the mmf generated by the control winding is equal to the mmf produced by the permanent-magnet in each magnetic circuit, the two gate windings will saturate their respective legs of the magnetic circuits at the same saturation angle of the a-c supply voltage half cycle and equal currents will flow in the two symmetrical gate winding circuits, assuming equal turns and resistance for the two circuits. With equal load resistors, R_L, the output current, I_o, through the load, R_o, will be zero. If the mmf generated by the control windings does not equal the mmf developed by the permanent-magnet, an aiding net flux will be developed in one magnetic circuit causing an earlier saturation angle and an opposing net flux in the other magnetic circuit causing a retarded

saturation angle. This action will result in an increase in current in one circuit gate winding and a decrease in current in the other. Thus there will be an unbalanced voltage drop across the equal load resistors, causing a net output current, I_o, to flow. The polarity of the output current will depend upon the polarity of unbalance between the mmf generated by the control windings and the permanent-magnet. The unit is therefore an error detector which utilizes a permanent-magnet as a reference. If this error current, I_o, is then used to control an amplifier, which provides the current source for the control current, a feedback loop is formed which provides a constant current or voltage system utilizing a permanent - magnet as a reference. A feedback loop for a constant voltage system is illustrated in the following block diagram.



2. Analysis of the magnetic reference circuit.[1]

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[1] Partially taken from a conference paper presented at the AIEE Summer and Pacific General Meeting, June 1954, Los Angeles, California. "A Magnetic Reference Unit", William Woodworth, dated 11 March 1954. [17].

The circuit to be analized is illustrated in Figure 10. The core itself is composed of 100% interlaced F type laminations of saturable magnetic material with the center leg broken by an air gap whose reluctance is approximately one tenth the reluctance of either outer leg. The purpose of the air gap is to prevent the shorting of the magnetic flux from the reference magnet. All the reluctance of each magnetic circuit is assumed to be across the outer legs of the three leg core since the core area of the other legs is made considerably larger by the use of added T laminations to the center leg. The purpose of these added laminations is to prevent interaction between the two magnetic circuits.

Considering one loop of the circuit of Figure 10 and neglecting the effects of the capacitors, the voltage across the gate winding for the unsaturated core may be written as

$$e_A = -L \frac{di}{dt} \tag{12}$$

Integrating, the current in the loop is given by

$$i = \frac{1}{L} \int_0^t - e_A \, dt = \frac{E_m}{\omega L} \left[1 - \cos \omega t \right] \tag{13}$$

for a sinusodial supply voltage if the d-c resistance of the circuit is assumed small compared to the inductive reactance. If the core material saturates at an angle α_s of the supply voltage with a current of i_o being just large enough to saturate the core, then

$$\alpha_s = \cos^{-1} \left[1 - i_o \frac{\omega L}{E_m} \right] \tag{14}$$

Let F_m be the mmf drop of the permanent-magnet flux across the end legs of the core and $N_c I_c$ be the d-c ampere-turns from the control wind-

ing opposing the mmf of the permanent-magnet. Now if we define i_d as the change of current in the gate windings required to saturate the core when there is a net direct mmf across the end leg, this current may be written from equation 8 as

$$i_d = \frac{F_m}{N_g} - \frac{I_c N_c}{N_g} \tag{15}$$

If $F_m = N_c I_c$ there will be no net flux nor a difference current and the saturation angle will be given by equation 14. If $F_m \neq N_c I_c$ the saturation angles for the two symmetrical circuits will be changed differentially and may be expressed as

$$\alpha_{s_1} = \cos^{-1} 1 - (i_o + i_d)\frac{\omega L}{E_m} \tag{16}$$

$$\alpha_{s_2} = \cos^{-1} 1 - (i_o - i_d)\frac{\omega L}{E_m} \quad . \tag{17}$$

The half-cycle wave form of the current in a gate winding, illustrated in Figure 11, will be similar to the wave forms of Figure 9 discussed in chapter II. The current wave form with the core in saturation is represented as i_L and is limited by the resistance of the loop. The current for the non-saturated core is represented as i_E, which is very small compared to the magnitude of i_L, and is primarily limited by the inductive reactance of the gate winding. The saturation angles when influenced by a net d-c mmf are represented as α_{s_1} and α_{s_2} as given in equations 16 and 17. Therefore, if we neglect the small exciting current, i_E, the d-c output current may be approximately determined by the average height of the area bounded by α_{s_1}, α_{s_2} and i_L .

The equivalent d-c circuit for one loop with the core in saturation is illustrated in Figure 12 and shows the division of current between the resistor, R_L, and the load, R_o. The loop current will be given by

$$I_g = I_L + I_o = \frac{E_{AVG}}{R_\ell} \tag{18}$$

where $R_\ell = \left[\frac{R_g}{R_L}\left(2R_L + R_o\right) + R_L + R_o\right]$

represents the d-c resistance around each loop and R_g is the sum of the d-c resistance of the gate winding, N_g, and the crystal diode forward resistance. The current division is given by

$$I_L = I_o \frac{R_o + R_L}{R_L} \tag{19}$$

and by substitution into equation 18

$$I_o = \frac{E_{AVG}}{R_e} \tag{20}$$

where

$$R_e = \frac{R_g}{R_L}\left(2R_L + R_o\right) + R_L + R_o \tag{21}$$

It then follows from equations 16 and 17 that the output current, I_o, will be given by

$$I_o = \frac{1}{2\pi}\int_{\alpha_{s_1}}^{\alpha_{s_2}} \frac{E_m}{R_e} \sin\alpha \, d\alpha \tag{22}$$

Combining equations 15 and 22 and substituting for R_e from equation 21 gives

$$I_o = \frac{\left(F_m - N_c I\right)\omega L}{\pi N_g\left[\frac{R_g}{R_L}\left(2R_L + R_o\right) + R_L + R_o\right]} \tag{23}$$

Equation 23 gives the output current as a function of control current, neglecting the effect of the shunting capacitors. Consideration of the capacitors shunting R_L complicates the analysis and their primary effect noted experimentally was to increase the output current for a given value of I_c by approximately 50% as shown in Figure 13. Figure 13 is a plot showing the variation of output current through a 500 ohm load with variations of control current for an experimental model constructed by the author. The value of the capacitor is not critical as long as the $R_L C$ time constant is large compared to the period of the supply voltage frequency.

Equation 23 denotes some interesting characteristics which result from the symmetry of the circuit of Figure 10. The output current is a linear function of the control current for a constant frequency. This is illustrated experimentally in Figure 13. The value of the control current which determines zero output is independent of the supply voltage frequency, which affects only the sensitivity of the unit. The output current is independent of the magnitude of the supply voltage as long as it has a sufficient magnitude to cause saturation of the core material during the a-c half cycle. The circuit itself is not critically dependent upon the core material used as long as it conveniently saturates during the a-c half cycle for the desired magnitude of a-c voltage.

Since the sensitivity of the magnetic reference unit is of importance for practical applications, it will be useful for design considerations to obtain an expression for the change of output current with changes of control current in terms of selectable design parameters.

Differentiating equation 23 with respect to the control current gives

$$\frac{dI_o}{dI_c} = \frac{N_c \omega L}{\pi N_g R_e} \tag{24}$$

Now, assuming the core material of one magnetic circuit loop to be of uniform cross sectional area, the inductance of an iron - cored coil subjected to an alternating magnetization corresponding to a maximum a-c flux density B_{max} in the iron is given for dimensions in inches as follows:[1]

$$\text{Inductance in henrys} = L = \frac{3.19 N_g^2 \times 10^{-8}}{\frac{l_i}{\mu a_i} + \frac{l_a}{a}} \tag{25}$$

where

N = number of turns

l_i = length of the magnetic circuit in iron

u = permeability of the magnetic material evaluated at the appropriate maximum alternating flux density B_{max}

a_i = cross section of the iron in the core

a_a = effective cross section of the air gap (will generally be somewhat greater than the measured cross section of the air gap because of the fringing flux).

l_a = length of the air gap

Thus for a core of selected material and dimensions, the inductance

[1] Radio Engineer's Handbook, F.E. Terman (McGraw - Hill Book Co. Inc.) 1943, Paragraph 25, section 2, page 97.

is given by

$$L = K N_g^2 \qquad (26)$$

where $K = \dfrac{3.19 \times 10^{-8}}{\dfrac{\ell_i}{\mu a_i} + \dfrac{\ell_a}{a_a}}$ = a constant. (27)

Combining equations 26 and 24 gives

$$\frac{dI_o}{dI_c} = 2K \frac{f N_c N_g}{R_e} \qquad (28)$$

and substituting for R_e from equation 21, rearranged, gives the change of output current for changes of control current,

$$\frac{dI_o}{dI_c} = 2K \frac{f N_c N_g}{2R_g + R_L + R_o\left[\frac{R_o}{R_L} + 1\right]} \qquad (29)$$

Equation 29 gives the sensitivity of the magnetic reference unit, neglecting the effect of the shunting capacitors, in terms of the frequency of the power supply, the number of turns on the control and gate windings, and the equivalent d-c loop resistance.

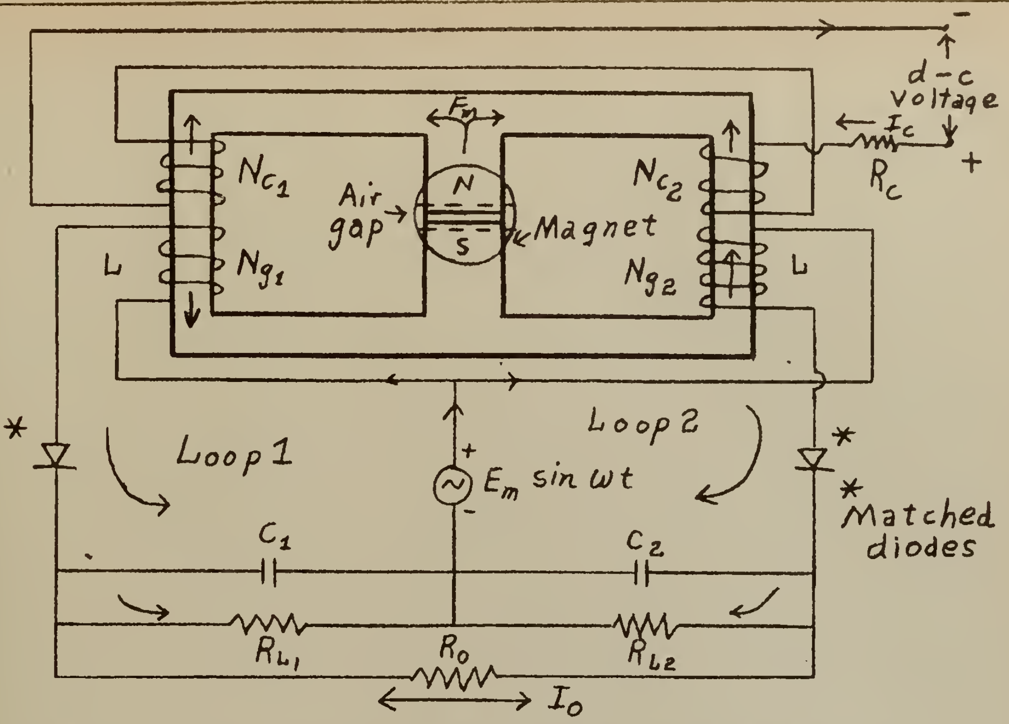

Figure 10. Circuit diagram of a magnetic reference unit.

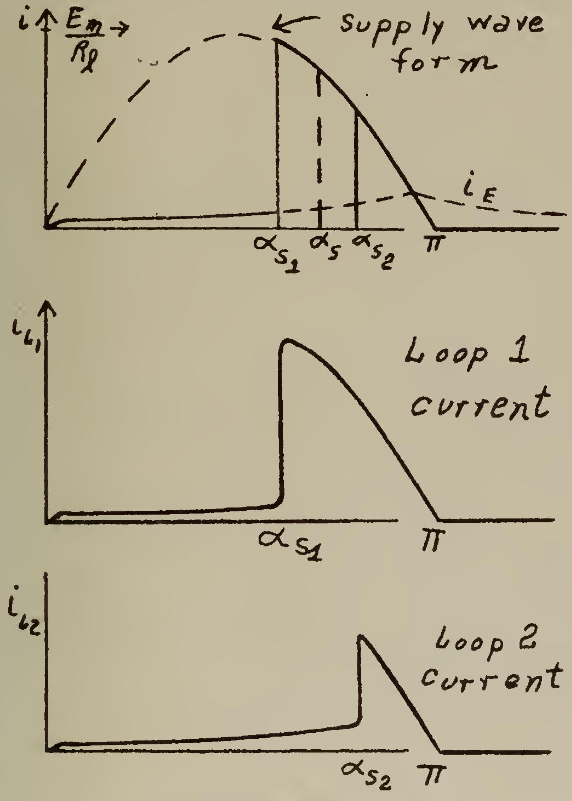

Figure 11.
Current wave forms.

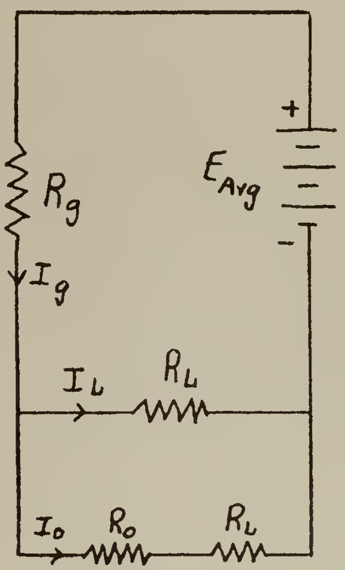

Figure 12

Equivalent d-c circuit for one loop with the core in saturation.

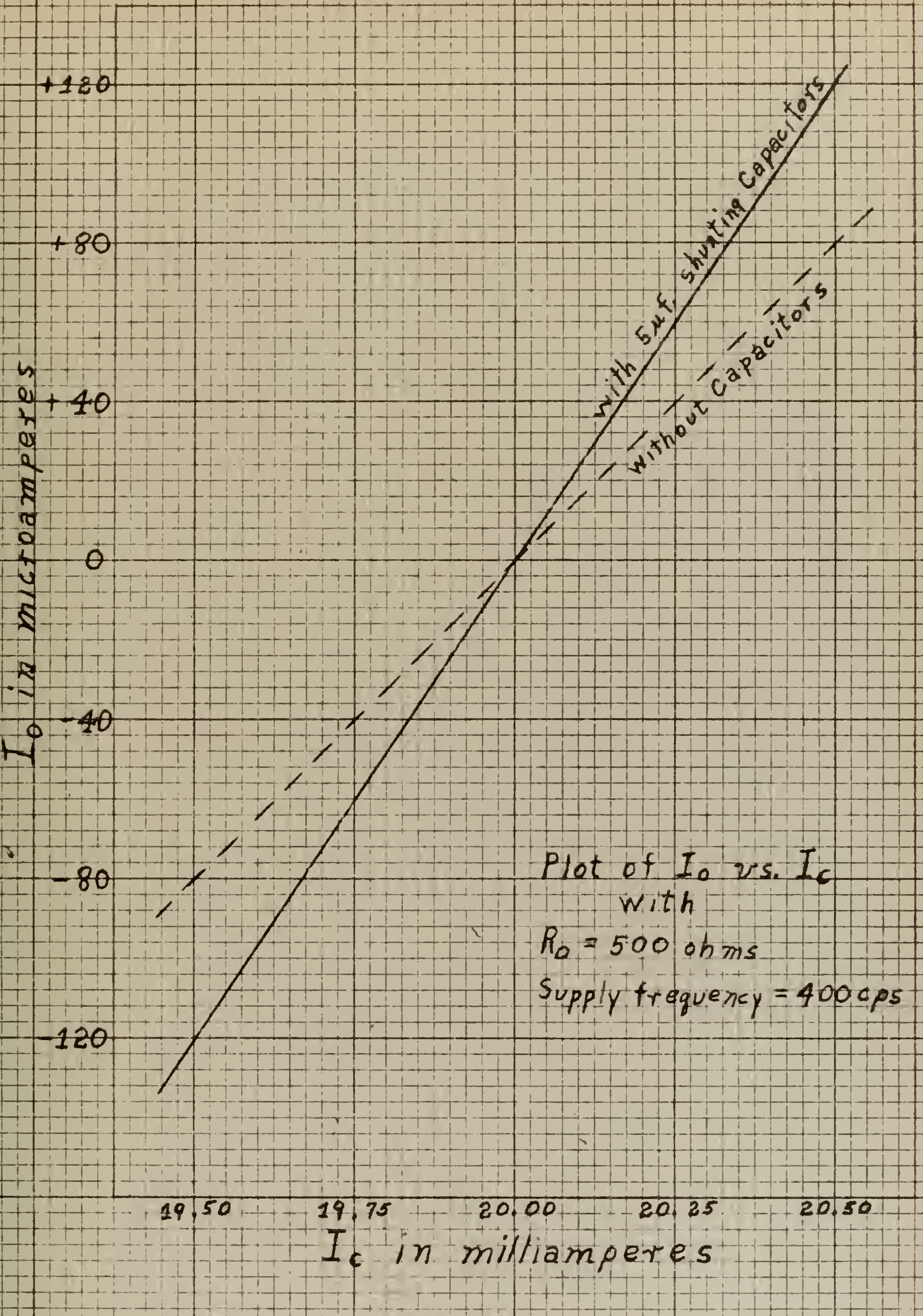

Figure 13

Response curves for an experimental magnetic reference unit.

CHAPTER IV

PRACTICAL DESIGN CONSIDERATIONS

The design of a magnetic reference unit will be influenced to some extent by the application to which the unit is to be applied, i.e., the load into which the unit will work, sensitivity requirements, control power available, a-c supply source available, weight and space limitations, and the environmental condition under which the unit must perform. The units constructed by the author for experimental purposes were designed with the consideration of utilizing the magnetic reference unit in a closed feedback loop with a high gain magnetic amplifier to form a stabilized power source of 10 volts (d-c) capable of supplying loads of 100 to 300 milliamperes in an environmental condition of variable temperature, vibration and relative humidity with an a-c power source of 35 volts (rms) at 400 cps frequency with variations of 10% in magnitude and frequency. The primary experimental efforts of the author were devoted to considerations of construction which might better permit the manufacturing of identical magnetic reference units within close tolerances without the requirements of excessively rigid manufacturing tolerances. These considerations of possible construction techniques will be pointed out where applicable.

It should be called to the readers attention that the design procedure presented in this paper cannot be expected to give exact results due to necessary approximations and estimates of expected values that are made. However, it is believed that the simplified straightforward

procedures provide a basis for a first trial design that will enable the design engineer to achieve the desired results.

1. Considerations of the magnetic circuit.

The magnetic circuit will be composed of a core of magnetic material with a permanent-magnet to induce the reference flux into the core material. From considerations of manufacturing and cost, the unit should be assembled from commercially available components. This suggests the use of an externally attached magnet to supply the reference flux to the core. Therefore the magnet will have to be placed across an air gap in order to prevent the shorting of the magnet flux. Two symmetrical electric circuits, to be discussed in a later paragraph, are utilized to provide an error current which is dependent on the reference flux. This factor leads to the requirement of two identical magnetic circuits with equal reference flux in each circuit. The foregoing considerations suggest the use of a three leg magnetic core with the permanent-magnet mounted across an air gap in the center leg and the windings of the electrical circuits placed on the two outside legs. Two magnetic circuits of equal characteristics may be formed with a minimum of interaction between the flux of the two circuits if the total reluctance of the magnet circuit can be approximately considered to occur in the outside legs, which support the windings of the electrical circuits. A core of magnetic material to meet the above requirements may be readily fabricated by the use of 100% interlaced F type laminations which are commercially available. These laminations permit the fabrication of a three leg core with an air gap in the center leg that may be spaced to give a satisfactory

compromise between reluctance and reference flux. The significant reluctance drop in the magnetic circuits may be concentrated in the outside legs by the addition of a few T type laminations to the center leg or the addition of a few I type laminations across the top and bottom of the three leg core since the center leg of the F laminations are of greater width than the other legs. The physical size of the laminations selected will be determined by the window area required for the electrical circuit windings.

By referring to equations 24 and 25 in Chapter III, it is noted that the sensitivity of the unit depends upon the gate winding inductances, which in turn depend upon the permeability of the core material to some extent. This suggests that a high permeability core material might be desirable. Also the core material must saturate during the half cycle of the a-c supply voltage for proper operation of the unit. The supply voltage required for saturation of the core material is given by the generally familiar equation

$$E_{(rms)} = 4.44 f N a_i B_{max} \times 10^{-8} \text{ volts} \tag{30}$$

where

f = frequency in cycles per second

N = number of turns

a_i = net core area

B_{max} = maximum flux density in lines per unit area .

In order to readily saturate the core material from the relatively low a-c supply voltage of 35 volts (rms), it was desirable to select a core material with a relatively low maximum flux density.

There are possibly other considerations of core materials which have been overlooked by the author. However, from the factors dis-

cussed, it is believed that a reasonable choice of core material may be made. From materials available, the author used 6 mil type 52 F laminations of hymu "80".[1] A unit was also assembled using size 52 F laminations of high permeability "49" metal[1] which gave comparable results with the hymu "80" core except that it required a higher saturation voltage due to a higher saturation flux density. It is suggested that the magnetic reference unit might also be designed to perform satisfactorily when constructed with lamination of silicon steel, although use of this material has not been verified experimentally by the author.

By reference to equations 23 and 29, we note that the magnitude of the reference flux, F_m, induced into the magnetic circuit by the permanent - magnet has an effect on the sensitivity of the unit and the power requirements of the control windings. The ampere-turns, I_cN_c, of the control windings must cancel the reference flux for the unit to give zero output. If the required control current is chosen at a relative low level to conserve power drain on the source, the strength of the reference flux directly determines the required control winding turns, N_c, which directly affect the sensitivity of the unit. The permanent - magnet should have a high coercive force, H_c, and a high retained residual flux, B_r, which does not significantly change with shock, vibration and temperature change for the normally expected environmental condition. It should also be of small physical size to be conveniently assembled with

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[1] Magnetic Metals Company, Camden 1, New Jersey.

the core laminations selected. The coercive force, H_c, is the amount of ampere-turns necessary to reduce the residual flux, B_r, to zero and is nearly a direct measurement of the force across an air gap. The merit or true strength of the permanent-magnet is the energy content per unit volume available to sustain flux in the external magnetic circuit and the product $B_r H_c$ is arbitrarily used as an indication of this energy content. Alnico permanent-magnets appear to give the best compromise between a high coercive force and high retentivity. [1]. Alnico is an alloy of aluminum, nickle, cobalt and iron. It is inexpensive, possesses a high resistance to stray fields and heat, and exhibits practically no loss of magnetization from shock or vibration.

In order to permit the manufacturing of identical magnetic reference units requiring the same value of control current to give zero output, it is desirable to be able to arbitrarily set the same value of reference flux in each unit constructed without the expensive procedure of requiring permanent-magnets matched to close tolerance. By utilizing a small permanent-magnet of round U configuration, the magnet may be rotated in place on the laminations across the air gap until the desired reference flux is established in the external magnetic circuit before securing it in place. The permanent-magnet used to produce the desired reference flux for the experimental units assembled by the author was a type 4Y9P4 Carboloy[1] Alnico Grade II round U permanent-magnet. An air gap in the center leg of the core of approximately three mils allowed

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[1] Trade Mark for the products of the Carboloy Department of the General Electric Company.

sufficient flux to be induced into the external circuit to obtain the desired reference flux and still permitted a small enough reluctance in the center leg with the added T laminations to prevent any noticeable flux interference between the two symmetrical magnetic circuits.

2. Considerations of the electric circuits.

With the components of the magnetic circuit selected, the performance of the magnetic reference unit will be determined by the characteristics of the electrical circuits. As previously mentioned in Chapter III, the electric circuits are composed of a d-c control circuit, two symmetrical a-c gate winding circuits, and a d-c load circuit. The schematic diagram for the electrical circuits is illustrated in Figure 14.

In the design of the d-c control circuit, we must consider the maximum value of reference flux obtainable from the permanent-magnet, the variation of magnet strength between different magnets, the change of input resistance to the control circuit with temperature variations, window area of the core available for windings, the sensitivity expected of the reference unit, and the current demands on the source of the control current. From a control current source that is capable of supplying a total of 300 ma load, if we arbitrarily select a d-c control current of 20 ma as a reasonable current value to provide zero output current, the number of control winding turns required to cancel the reference flux may be determined. From experimental measurements it was found that approximately 18 ampere-turns were required in the control windings to cancel the maximum value of reference flux induced into the selected

magnetic circuit by the 4Y9P4 magnet. Therefore the maximum number of control winding turns for each magnetic circuit would be 900 turns. In order to allow for variations in strength between different magnets of the same type that we would expect in quantity manufacturing, let

$$N_c = 800 \text{ turns}$$

giving

$$I_c N_c = 16 \text{ ampere-turns for each magnetic circuit.}$$

Thus we may now rotate the round U magnet in order to establish a reference flux in the core material that establishes zero output current when it is opposed by 16 ampere-turns from the control winding. In order to maintain balanced cancellation of the reference flux in the two magnetic circuits, equal number of turns on the control winding bobbins is important. Since the d-c resistance of the copper wire of the control windings will change with temperature variations, it is desirable to have a low d-c resistance in the coil to simplify temperature compensation of the coil resistance. Therefore number 31 heavy formvar copper wire was used for the control windings. By utilizing equations developed in Chapter III to give range of magnitude values for the a-c gate winding circuits, a first approximation design may be completed. The gate winding turns are primarily dependent on window area of the core available for the windings, the wire size, the cross sectional area of the core, and the relationship between the maximum alternating flux density in the core and the rms value of the required saturation sinusoidal voltage. For selecting the number of gate winding turns the author used the approach of fitting the gate windings to the winding area available with the chosen

core configuration, then solving for the required number of laminations for a chosen value of saturation voltage, using equation 30. A one inch nylon bobbin with an available winding area of .187 square inches (238,000 circular mils) was used to support the windings. Allowing 25% of the total winding area for insulation wrappings and lead connections, there are 178,000 circular mils of area available for the control and gate windings. Using 86,400 circular mils for the control winding leaves 91,600 circular mils for the gate winding. The wire size required for the gate windings can be determined from the required current carrying capacity. The value of the gate winding resistance plus the forward resistance of the diode was estimated at 700 ohms. For a load, R_o, of 500 ohms and R_g of 700 ohms, a theoretical plot of equation 21 is shown in Figure 15 for variation of R_L. This would suggest a value of R_L of approximately 600 ohms due to the effect of R_e upon the sensitivity noted in equation 28. Using these values the equivalent d-c resistance around each loop, R_ℓ, would be approximately 1,090 ohms. For a 35 v (rms) power supply and complete saturation of the core over the a-c half cycle, the maximum current (rms) that would be carried by a gate winding would be approximately 22.7 milliamperes, given by

$$I_{(rms)} = \frac{E_{rms}}{\sqrt{2}\,R_L} \tag{31}$$

Allowing one circular mil per milliampere of current for the current carrying capacity of copper wire, number 38 heavy formvar copper wire with an average cross sectional area of 23 circular mils was selected for the gate windings.

Then

$$N_g = \frac{\text{available winding area}}{\text{wire area}} = \frac{91600\,\text{C.M.}}{23\,\text{C.M.}} = 4000\,T \quad (32)$$

The theory of operation of the magnetic reference unit covered in Chapter III was based on the premise of symmetrical gate winding circuits. This would suggest the requirement of equal gate winding turns, low forward resistance or matched diodes, and d-c resistances in the two gate windings as well as resistors R_L matched to close tolerances. The diodes should also have high back resistance to prevent significant demagnetizing effect on the cores, which would result in an unbalance of the required symmetrical operation.

From manufacturer's data the maximum flux density of hymu "80" is given as approximately 8000 gauss (51.6 Kilolines per square inch). Selecting a saturation voltage in the vicinity of 30 volts (rms) to ensure saturation of the core during the half cycle of the a-c supply, we obtain the magnitude of net area required from equation 30,

$$a_i = \frac{E_{(rms)} \times 10^{-8}}{4.44\,f\,N_g\,B_{max}} \quad (33)$$

A core constructed of seven type 52F six mil laminations in the end legs gives a cross section area of 78.75 X 10^{-4} square inches. The saturation voltage is predicted as

$$E_{(rms)} = 4.44\,f\,N_g\,a_i\,B_{max} \times 10^{-8}\ \text{volts} = 29\ \text{volts} \quad (34)$$

An estimate of the sensitivity of the designed unit, neglecting the effect of the shunting capacitors, may be predicted from equation 29

after determining a value for the constant K, equation 27. From the assumption that the significant reluctance of each magnetic circuit is concentrated in the end legs of the magnetic core, equation 27 may be rewritten as

$$K = \frac{3.19 \times 10^{-8} \mu_i a_i}{l_i} = 2.01 \times 10^{-7} \qquad (35)$$

where

u_d = 1000 = approximate effective design permeability
l_i = 1.25 inches = mean path length in end leg
a_i = 78.75 X 10^{-4} square inches = net cross section of end leg.

Thus

$$\frac{dI_o}{dI_c} = 2K \frac{f N_c N_g}{2R_g + R_L + R_o\left[\frac{R_g}{R_L} + 1\right]} = .167 \qquad (36)$$

It should be noted that the primary variable determining the maximum sensitivity obtainable is the turns on the control winding, which are limited by the maximum value of reference flux that can be obtained in the core material.

3. Considerations of environment.

Factors due to environment which may affect the performance of the magnetic reference unit are temperature, shock, vibration, humidity, and stray magnetic fields. The most significant effects are due to stray magnetic fields and variations of temperature. It was found necessary to enclose the unit in a shielding can of magnetic metal to prevent the

induction of stray flux into the core material from stray magnetic fields. Any small effects from shock, vibration, and humidity may be minimized by potting the reference unit in a suitable potting material, which can also serve the purpose of holding the unit in a fixed position inside the shielding can. Effects of change of temperature and methods of minimizing these effects are discussed in the following paragraphs.

The change of the air gap spacing, which affects the value of the reference flux, F_m, with changes of temperature, must be minimized to a negligible value. One remedial approach to this problem is to support the laminations with supports made of material that has the same thermal coefficient of expansion as the lamination material. From a manufacturing viewpoint this method has the disadvantage of requiring very precise machineing and assembly of the supporting frame in order to set the appropriate air gap and have this air gap remain constant with thermal expansion of the laminations and supporting frame. A method of assembly used by the author to provide a constant air gap with changes of temperature from -50°C to +80°C consisted basically of forcefully preventing the expansion of the core material. The assembled laminations were clamped between the supports and the air gap length established by placing a piece of 3 mil paper in the air gap space. The assembled core was impregnated with Glyptal clear varnish under 28 inches of vacuum. The varnish was then hardened by baking at 65°C. After being mounted in place and adjusted to provide a reference flux that could be cancelled by 20 milliamperes of control current, the round U permanent-magnet was secured in place with a thin film of cement. The magnetic reference unit

constructed by this method of core assembly gave zero output current with 20 milliamperes of control current over the desired temperature range, indicating a constant air gap. The core assembly with magnet and windings is shown in Figure 16. This method of assembly has the advantage of providing a simple method of manufacturing. It also admittedly has the undesirable result of causing strains in the core material with temperature change. However, it is recalled from Chapter III that the circuit is not critically dependent upon the core material as long as it conveniently saturates during the a-c half cycle of the supply voltage and symmetry is maintained. There may also be some question as to the effect of possible slow annealing of the core material over a long period of time due to the presence of the strain in the material if the reference unit is operated in a constant temperature region such as + 80°C. The author cannot give a conclusive answer to this question at this writing. However, it is believed that the method does provide such a simple and inexpensive means of manufacturing that further long term tests to determine its effectiveness is warranted. Another effect on the reference flux that can result from temperature change is a change in the strength of the permanent-magnet. However, this change of permanent-magnet strength is small over the temperature range of -50°c to + 80°C for an Alnico magnet.

With the establishment of a constant reference flux, the largest effect on the magnetic reference unit due to a change of temperature is the change of resistance of the control windings. This effect requires the inclusion of a negative temperature-coefficient network of resis-

tors in series with the control winding to effectively compensate for this change of resistance. The network may be composed of a temperature-sensitive element which has a negative temperature coefficient, such as thermistors or special types of ceramic resistors, and fixed resistors. The fixed resistors are used to shape the characteristics of the temperature-sensitive element so that the desired characteristics for the compensating network are obtained. One method [12] of calculating the resistor components required to shape the characteristics of the temperature-sensitive element consists of approximating the curve of R_T plotted as a function of r_T by a rectangular hyperbola, where

R_T is the desired temperature characteristic of the network and

r_T is the characteristic of the temperature-sensitive element alone.

The resistance of the temperature compensating network of Figure 14 may be expressed as

$$R = \frac{R_2 R_3 + R_2 r}{(R_2 + R_3) + r} \tag{37}$$

which is of the general form of

$$R_T = \frac{a + b r_T}{c + r_T} \tag{38}$$

where a, b, and c are positive coefficients. Equations (37) and (38) are identical if

$$R_2 = b \tag{39}$$

$$R_3 = c-b \tag{40}$$

The procedure for determining the value of the positive coefficients b and c basically consists of the following steps.

(1) From a plot of the resistance of the control windings as a function of temperature, determine the desired temperature characteristics of the network to provide temperature compensation.

(2) Plot R_T as a function r_T with R_T as the ordinate and r_T as the abscissa.

(3) Select three points on the curve plotted in step (2) and construct a rectangular hyperbola passing through these three points.

(4) Determine the asymptotes, which are the coefficients b and c, of this hyperbola in terms of R_T and r_T coordinates respectively and the intersection of the hyperbola with the R_T axis which determines the ratio a/c.

The effect of temperature change on the symmetrical gate winding circuits is limited to the differential temperature characteristics of the semi-conductor diodes due to the symmetry of the circuit. This effect may be minimized by the use of silicon diodes or if germanium diodes are matched for similar temperature characteristics.

4. Considerations of the magnetic amplifier.

As previously stated, the magnetic reference unit is an error detector device and must be used with an amplifier to form a regulated voltage supply. This amplifier should satisfy the requirements of high power gain and reliability, and should be able to furnish the desired power output. A self-saturated magnetic amplifier circuit with external positive feedback satisfies these requirements very well. Magnetic

amplifiers with infinite gain at three points on their control characteristics have been designed [5] which have very high gain when controlled within the limits of their operating range. This type of amplifier is well suited for use with the magnetic reference unit. When used with the magnetic reference unit to form a constant voltage supply, the magnetic amplifier, as well as the reference unit, will also be affected by temperature change. This effect of temperature change will cause changes in the output voltage with changes in temperature, but they can be minimized by proper design and compensation of the amplifier so that the temperature compensating network of the control winding of the magnetic reference unit forms the overall compensating network of the constant voltage supply.

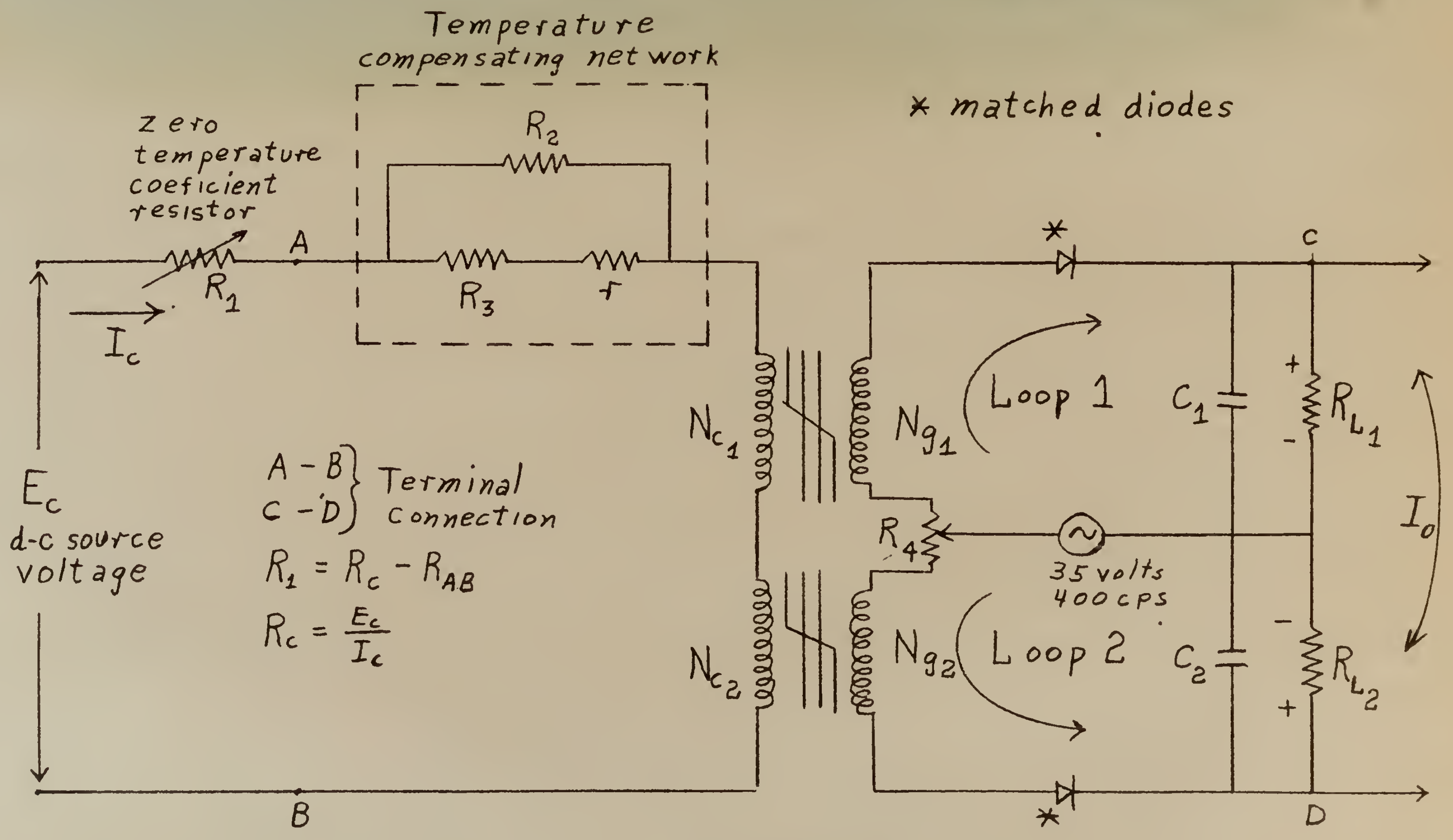

Figure 14

Schematic diagram for a magnetic reference unit

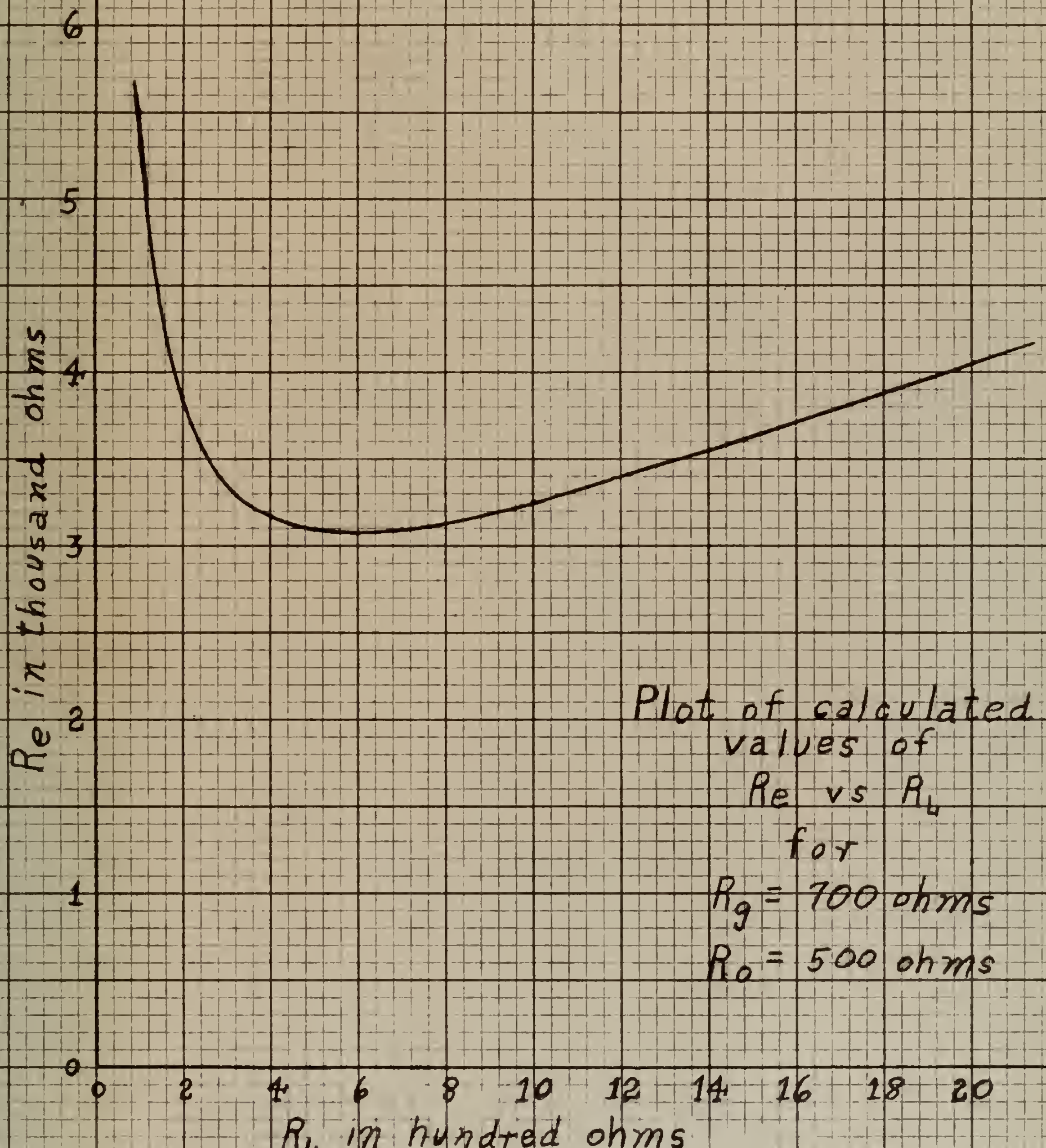

Figure 15.

Theoretical plot of R_e vs R_L

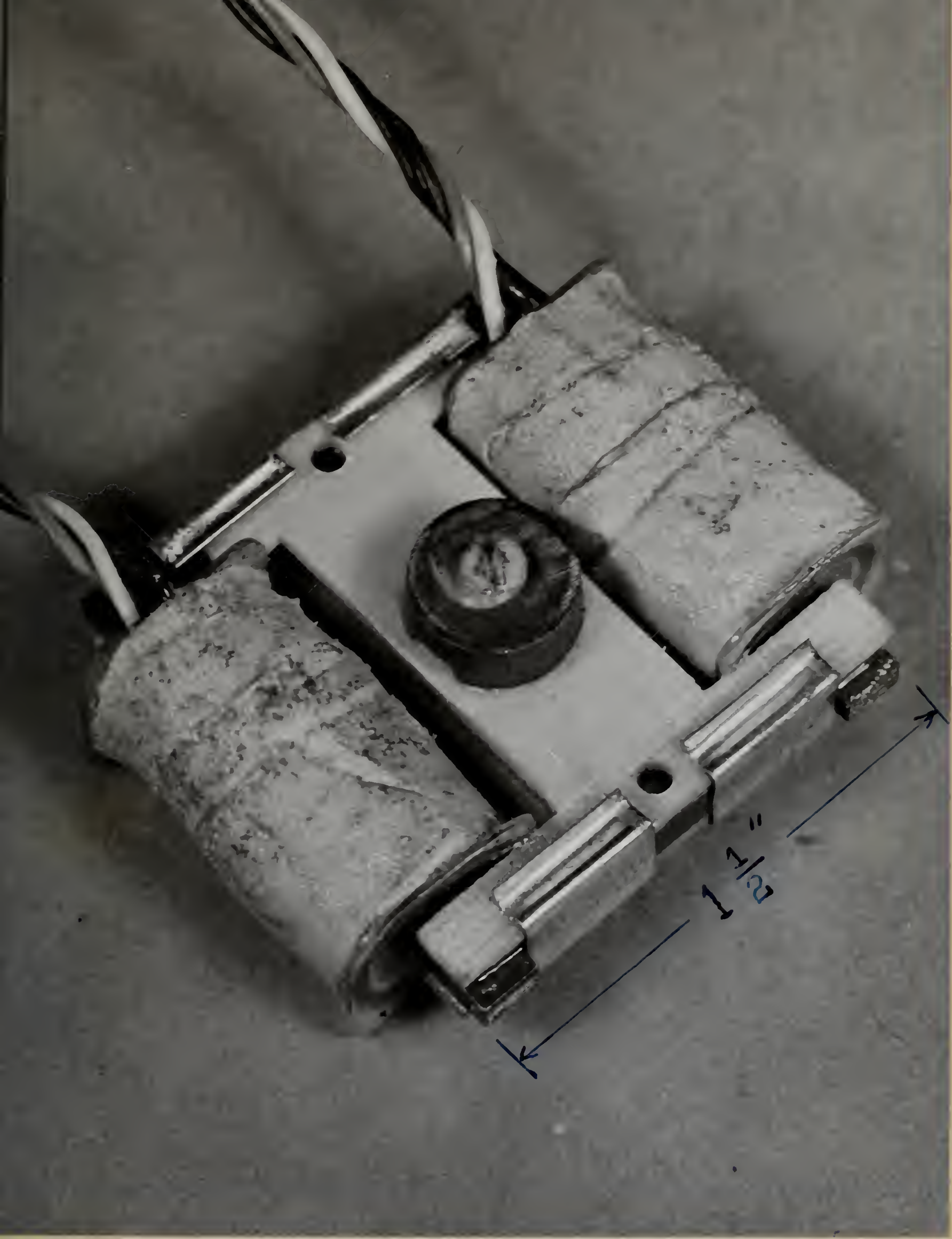

Figure 16. Magnetic reference unit core assembly

CHAPTER V

CONSTRUCTION TECHNIQUES AND TEST RESULTS

In Chapter IV, some mentions were made of construction techniques along with the discussions on design considerations, when it was believed that these techniques had an influence on component choice or configuration. The intent in this chapter is to present, without undue repetition, a summary of construction techniques evolved during the construction and testing of several magnetic reference units by the writer while on an industrial tour with the Pacific Coast Division, Aerovox Corporation, Monrovia, California.

The primary problems to be considered by a manufacturer of the magnetic reference unit discussed in this paper are

(1) to provide a constant reference flux of selected magnitude in the magnetic core under conditions of changing environment and

(2) to obtain symmetry to close tolerances in the gate winding circuits.

Techniques to solve the first of these two problems were discussed in Chapter IV. The second may be broken down into the problems of providing equal turns and resistance in the gate windings, equal resistance characteristics for the diodes, and matched resistors R_L. Tests showed that the resistors R_L would have to be matched to approximately .01%. Using 649.5 ohm resistors in the circuit, a change of .07 ohms of unbalance gave a noticeable output current of approximately 2.5 microamperes into a 500 ohm load. With five microfarad capacitors in the cir-

cuit there was only a small variation of sensitivity for values of R_L ranging between 600 and 4000 ohms with the best sensitivity obtained with about 1800 ohms. Due to the filtering actions of the capacitors, this did not strictly agree with the theoretical predictions of Figure 15 where the effects of the capacitors were neglected. However, it did substantiate the prediction that an optimum range of values does exist.

From considerations of size and stability over the environmental temperature range, tantalum capacitors appear to be the most suitable selection for the shunting capacitors.

The diodes used were silicon junction diodes with the unique property of a low forward resistance (40 ma forward current with 1.5 volts across the diode) and a high back resistance exceeding 10 megohms. These diodes meet the circuit requirements very well but have the disadvantage of being relatively expensive. It is also believed that the gold bonded variety of germanium diodes could be successfully employed.

Test results demonstrated that matching of the gate winding turns as well as gate winding resistance is important. For windings with d-c resistances in the range of 500 ohm magnitudes, it was necessary to match resistances to within about 0.1 ohms. Also it was noted that an unbalance of two turns for 3000 turn gate windings produced the same results as an unbalance of approximately 0.1% of the gate winding circuit resistance. In order to alleviate the necessity of matching both gate winding turns and resistance during fabrication, a small potentiometer on the order of 10 ohms value is incorporated in the circuit, illustrated as R_4 in Figure 14. For machine wound layer windings a smaller value po-

tentiometer can probably be utilized.

A simple method of assembly and circuit balancing by which reproducible magnetic reference units similar to the design presented in Chapter IV may be constructed is outlined as follows.

(1) Layer wind the control and gate windings to exact design turns on the winding bobbin, i.e. $N_c = 800$ turns and $N_g = 4000$ turns for the design presented.

(2) Assemble the laminations and two bobbins to provide a three leg core with windings on the outside legs and the desired air gap in the center leg.

(3) Place the assembled core in its shielding can and connect the gate winding leads to the symmetrical external electric circuit.

(4) With a sensitive galvanometer or millivolt meter connected to the output leads (point C and D of Figure 14) adjust R_4 to give zero output. This procedure will provide symmetrical resistive circuits. When the resistance is properly matched, variations of supply voltage magnitude within the limits of saturation requirements will not change the output from its zero value.

(5) Place the round U magnet across the air gap and replace the assembled core in its shielding can. Connect the control winding leads to the control circuit.

(6) Set the control current by adjusting the value of R_1 of Figure 14 to the value selected to provide zero error output current ($I_c = 20.00$ ma) and then rotate the round U magnet with a nonmagnetic screwdriver through a hole in the shielding can to es-

tablish the reference flux required to give zero output.

The foregoing procedures establish the required symmetrical electrical circuits and the desired level of reference flux. A magnetic reference unit was constructed according to the design presented in Chapter IV and assembled by the above procedures. A summary of circuit components and selected parameters are listed as follows:

$N_{c1} = N_{c2} =$ 800 turns #31 heavy formvar copper wire.

$N_{g1} = N_{g2} =$ 4000 turns #38 heavy formvar copper wire.

$R_4 =$ 10 ohm potentiometer.

$C_1 = C_2 = 5$ uf

$R_{L1} = R_{L2} = 1995.5 \pm .2$ ohms.

core: Fourteen type 52F 6 mil hymu "80" laminations.

Sixteen T type 6 mil hymu "80" laminations.

air gap: 3 mils.

magnet: 4Y9P4 Carboloy Alnico II round U.

$I_c =$ 20.00 ma d-c reference current.

a-c supply voltage = 35 volts (rms), 400 cps.

The sensitivity curves for this reference unit are plotted in Figure 13. The reference unit also provided zero output current for a 20 ma control current over the temperature range -50° C to+ 80° C and for 10% variations of supply voltage. This magnetic reference unit, incorporated in a closed feedback loop with a high gain self-saturated magnetic amplifier voltage regulator designed to furnish a stabilized 10 volt d-c power source for load variations of 100 to 300 milliamperes, can provide regulation within 0.5% over a wide range of environmental conditions.

CHAPTER VI

CONCLUSIONS

The magnetic reference unit presented in the preceding chapters permits the formation of a basic reference based upon a dependable permanent-magnet. This reference unit can be combined with any high gain magnetic amplifier to form a constant source of voltage or current which may range from small to very large values depending on the design of the amplifier circuits. Both the reference unit and the magnetic amplifier circuits are composed of stable static elements that provide a high degree of reliability.

Some other devices that are more or less commonly used for reference purposes are the gaseous voltage regulator tube, a thyrite network, the saturating transformer and the reference voltage silicon junction diode. Basically, the primary limitation of all regulator circuits depends upon the difficulty of obtaining a completely stable reference device for the desired operating conditions. The gaseous voltage regulator may stabilize at slightly different values when switched off and on again and has limited reliability under conditions of shock and vibration. The thyrite network has a slow response time and is suitable over a smaller ambient temperature range. The saturating transformer is sensitive to changes of both supply voltage frequency and temperature, which may be minimized by suitable compensation. The reference voltage diode is a relatively new device [3] and like the magnetic reference unit has not yet attained wide application. It is also sensitive to changes in ambient temperature,

the degree depending on the characteristics of the individual diode. It has the advantages of small size, low power consumption and a promise of long life.

The primary disadvantage of the magnetic reference unit is also sensitivity to temperature change, which can be minimized over a wide temperature range by the use of a simple resistance compensation network. Since the circuits of the reference unit are basically composed of two parallel simple half-wave saturable reactor circuits, it will also have an inherent minimum time delay of one half-cycle of the supply voltage frequency.

It is believed that the problems of economically producing a standard magnetic reference unit as a marketable item can be solved by use of construction techniques similar to those presented in this paper. With the development of a standard marketable unit, the magnetic reference unit can become another useful device for application to electronic circuits.

It is not the intent of this writer to advocate the acceptance of one basic component device as a replacement for others. Saturable-reactor devices as well as tubes and semi-conductor devices are available for application in the broad field of electronics. The design engineer should have a familiarity with each of these devices and consider the suitability of each to meet the specific application requirements.

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